

Solar System Exploration Division Strategic Plan

*Preparing the way
to the new frontier
of the 21st century*

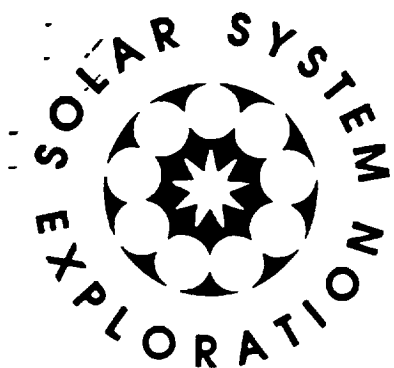
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Solar System Exploration Division Strategic Plan

Volume I Executive Summary & Overview

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Executive Summary and Overview

Preface

This six-volume series presents the Solar System Exploration Division's Strategic Plan for the 10-year period FY 1994 to FY 2003. The plan recognizes the competing pressures of "restriction" (such as the FY 1991 Budget Deficit agreement between the President and Congress) and "ambition" (such as a Mission from Planet Earth planning augmentation) and provides the necessary flexibility to deal with both.

Our strategic response is characterized by five fundamental precepts: (1) execute the current program, (2) improve the vitality of the program and the planetary science community, (3) initiate innovative, small, low-cost planetary missions, (4) initiate new major and moderate missions, and (5) prepare for the next generation of missions.

This Strategic Plan describes in detail our proposed approach to accomplish these goals. Volume I, in the pages that follow, provides first an Executive Summary of highlights of each of the six volumes, and then goes on to present an overview of the plan, including a discussion of the planning context and strategic approach.

Volumes II, III, IV, and V describe in detail the initiatives proposed. An integral part of each of these volumes is a set of responses to the mission selection criteria questions developed by the Space and Earth Science Advisory Committee. *Volume II, Mission From Planet Earth*, describes a strategy for exploring the Moon and Mars and sets forth proposed moderate missions — Lunar Observer and a Mars lander network. *Volume III, Pluto Flyby/Neptune Orbiter*, discusses our proposed major new start candidate for the FY 1994 to FY 1998 time frame. *Volume IV, Discovery*, describes the Near-Earth Asteroid Rendezvous, as well as other candidates for this program of low-cost planetary missions. *Volume V, Toward Other Planetary Systems*, describes a major research and analysis augmentation that focuses on extrasolar planet detection and the study of planetary system processes. Finally, Volume VI summarizes the technology program that the division has structured around these four initiatives.

This 10-year plan is a measured response to the exploration challenges we now face, yet it is also compelling and exciting. It provides for completing the reconnaissance of our own solar system; the continued systematic exploration of the inner planets, outer planets, and small bodies; and the expansion of the division's horizon to include the search for planets around other stars. The plan also provides for the renewed vitality of the planetary science community and is responsive to the recommendations of the Advisory Committee on the Future of the U.S. Space Program regarding Mission from Planet Earth.

Executive Summary

America's solar system exploration spacecraft are flying again. The Magellan mission is actively mapping the hidden surface of Venus. In the next few years, new missions will begin detailed explorations of Mars, Jupiter, Saturn, Saturn's large moon Titan, and Comet Tempel 2. It is now time to plan the next stages in humanity's exploration of the solar system — *to prepare the way to the new frontier of the 21st Century*.

This new exploration is based on the knowledge, confidence, and experience of three decades of exciting and successful planetary achievements, when American spacecraft visited every planet in the solar system except Pluto. In the coming decade, the planetary program will continue this balanced thrust of solar system exploration and begin the search for other planetary systems. It will also play a leading role in the early phases of Mission from Planet Earth. As a result, planetary exploration of the Moon and Mars will have a special emphasis: *to carry out exciting scientific missions that will, at the same time, provide the information needed to plan the subsequent human exploration of these worlds*.

This document, like the OSSA Strategic Plan of which it is a part, provides a 10-year vision and a specific 5-year plan of new mission starts and ground-based initiatives for the period FY 1994-1998. Initiatives proposed for FY 1993 are also included because of the potential necessity to carry them over into the FY 1994-1998 time frame. The plan also identifies a group of additional missions (in no priority order) for initiation after 1998, so that essential studies and technology development for them can be started in the next few years.

The solar system exploration component of the OSSA Strategic Plan consists of a balanced program of major, moderate, and small missions, combined with essential ground-based activities and Earth-orbiting payloads. Table 1 summarizes the Solar System Exploration Division's near-term recommendations for both the Core Science Program and for a possible Mission from Planet Earth augmentation.

The planetary exploration program will retain its traditional scientific goals: to explore the solar system, to understand its origin and the evolution of planets, and to understand the environment for life. The program will utilize several complementary approaches: a strong research program, a systematic exploration of the solar system with flight missions, the identification and development of new technical capabilities for planetary science and exploration, the expansion of an instrument development program for flight missions, and studies of advanced mission concepts. The program will continue the broadly based evolutionary character of individual flight missions, from *Reconnaissance* (flybys), through *Exploration* (orbiters and simple landers), to *Intensive Study* (sophisticated robotic missions and human presence).

Components of this program for FY 1994-2003 are summarized in this volume and described in more detail in the accompanying volumes. Specific near-term thrusts of the program are:

- To begin the planetary exploration component of Mission from Planet Earth with robotic missions to the Moon (Lunar Observer) and Mars (Mars lander network) and by technical studies of appropriate follow-on missions to each planet. (Volume II)
- To complete the reconnaissance of the solar system with a Pluto Flyby mission to explore the most distant planet and its strange moon Charon. This will be combined in a single, dual-spacecraft project with a Neptune Orbiter and Probe mission to make a detailed, long-term study of the Neptune system, including its large moon Triton. (Volume III)
- To begin the exploration of the solar system's small objects (comets and asteroids) with a Near-Earth Asteroid Rendezvous (NEAR) mission, which will also initiate the Discovery Program, a series of simple, cost-effective, small-spacecraft missions with focused scientific goals. (Volume IV)
- To start humanity's first intensive search for planets around other stars by combining ground-based research with currently feasible technical developments into a long-term program of ground- and space-based efforts called Toward Other Planetary Systems (TOPS). (Volume V)
- To identify and develop, in cooperation with NASA's Office of Aeronautics, Exploration and Technology, the technologies required to carry out more intensive and sophisticated explorations now being studied for the years beyond 2000 — advanced propulsion, planetary surface rovers,

Table 1. Solar System Exploration Division Near-Term Recommended OSSA Program Strategy, FY 94-FY98.

Core Science Program

Major Missions	Moderate Missions	Small Missions	Mission Operations & Data Analysis	Research Base Enhancements
Pluto Flyby/ Neptune Orbiter	Mars Lander Network* (MESUR) Lunar Orbital Survey* (Lunar Observer)	Discovery Program: Near Earth Asteroid Rendezvous	Magellan Extended Mission Mars Observer Augmentation* Multimission Software Transition Venus Data Analysis Asteroid Data Analysis Mars Data Analysis Outer Planet Data Analysis	Toward Other Planetary Systems Advanced Computation and Visualization Instrument Development Augmentation Centers for Laboratory Studies Planetary Systems Science

*to be implemented within Core Science Program if MFPE is delayed

SSSD Contribution to Mission From Planet Earth

Major Missions	Moderate Missions	Small Missions	Mission Operations & Data Analysis	Research Base Enhancements
	Mars Lander Network* (MESUR) Lunar Orbital Survey* (Lunar Observer)		Mars Observer Enhancement	Science Definition Studies

*to be implemented within Core Science Program if MFPE is delayed

Earth Orbital/Platform Payloads

Space Shuttle	Space Station Freedom	Unmanned Platforms
	Cosmic Dust Collection Facility	

sample return missions, Mercury orbiters, Venus surface landers, and a new generation of instruments and optical facilities for use in Earth orbit or on the surface of the Moon. (Volume VI)

Based on scientific and technical readiness, it is recommended that this program be implemented with new starts as follows:

- **FY 1993:** Initial ground-based phase of the TOPS program (TOPS 0) initiated by constructing the Keck II Telescope in Hawaii and establishing a ground-based research and technology development effort.
- **FY 1994:** Lunar Observer development started to support an established Mission from Planet Earth program by carrying out a global scientific mapping of the Moon.
- **FY 1994:** Small-mission Discovery Program established with a Near-Earth Asteroid Rendezvous (NEAR) new start. Subsequent Discovery candidate missions include Earth-orbiting planetary telescopes, a Venus Atmospheric Probe, a Mars Aeronomy Orbiter, a Lunar Aeronomy Orbiter, and a Phobos/Deimos Probe.
- **FY 1995:** Mars Environmental Survey (MESUR) begun to support Mission from Planet Earth investigations of Mars by gradually establishing a global scientific network of landed stations over the martian surface.
- **FY 1996:** Major exploration effort initiated for the outer solar system: dual Mariner Mark II missions to make the first reconnaissance of Pluto (Pluto Flyby) and to extend exploration of the outer solar system beyond Saturn (Neptune Orbiter and Probe).
- **FY 1997:** Begin the Cosmic Dust Collection Facility for flight on Space Station Freedom or a free-flying platform; initiate a follow-on Discovery mission, possibly an Earth-orbiting planetary telescope.

The planetary program will support these new missions by systematically strengthening and expanding its essential ground-based activities: Research and Analysis, Mission Operations, and Data Analysis. A series of focused efforts will be established during the next several years to help restore these activities to full vigor and to adapt them to the new demands of future exploration. These initiatives will be specifically designed to produce major scientific yields with modest resources, especially in new areas of interdisciplinary science.

Research base enhancements include: Toward Other Planetary Systems Phase 0 (FY 1993), Advanced Computation and Visualization (FY 1994), Instrument Development Augmentation (FY 1995), Centers for Laboratory Study (FY 1996), and Planetary Systems Science (FY 1997).

In the *Mission Operations* area, initiatives (all for FY 1993) include the Magellan Extended Mission, an essential augmentation to Mars Observer operations, and an initiative to transition mission operations into the modern com-

puter era (Multimission Software Transition).

The *Data Analysis* initiatives, matched closely to the timing of data returns from current and future missions, include: Venus Data Analysis (FY 1993), Asteroid Data Analysis (FY 1994), Mars Data Analysis (FY 1995), and Outer Planets Data Analysis (FY 1996).

This combined program of space missions and ground-based activities will extend into the next century one of the most exciting, successful, and visible explorations in human history.

Mission From Planet Earth

The emphasis on the Moon and Mars in Mission from Planet Earth presents special challenges to the planetary program to explore, characterize, and understand these worlds. The program's goal is to carry out an exciting scientific exploration effort, which also supplies the information needed to plan on-site human exploration of these worlds. Much of the needed information—high-resolution imagery, physical and chemical information about surface materials, the nature and location of water and other volatiles, the atmospheric dynamics of Mars, and clues to the existence of living and fossil life on Mars—is essential both to answer critical questions about the Moon and Mars and to plan the future human exploration of these worlds. At the same time, the solar system exploration program will be involved in identifying and planning the scientific work to be done by humans on the Moon and Mars.

In exploring the Moon, the next step should be Lunar Observer, a polar-orbiting spacecraft to obtain a global scientific inventory of the Moon's surface composition, topography, and gravitational and magnetic fields. Current studies are evaluating whether this mission can best be done with a single spacecraft, a descendant of the currently developed Mars Observer, or by a series of smaller spacecraft that could be accommodated within the "go-as-you-pay" philosophy proposed for Mission from Planet Earth. Initial studies are under way to define subsequent lunar missions to be carried out both before and during the period of human occupancy. Surface roving vehicles, surface geophysical networks, and sample return missions are all being evaluated.

Planning for the exploration of Mars is being undertaken in a similar evolutionary way. Mars Observer, scheduled for launch in September 1992, will provide a long-term global data base for the planet's surface and dynamic atmosphere. An enhancement to the ground processing capability for the Mars Observer camera could yield a significantly larger data base of high resolution images for landing site studies. The next step in the flight program is a Mars Environmental Survey (MESUR) to establish a network of surface stations on Mars. This mission, which would emphasize surface composition, internal structure, and surface weather measurements, can

be done in a gradual way over several launch opportunities, also in a "go-as-you-pay" manner.

Subsequent Mars missions are now being studied. The preferred scientific missions — surface rovers and sample returns — are complex and technically challenging. An active effort will involve the examination and development of microtechnologies that could miniaturize the equipment, enable the use of smaller launch vehicles, and reduce mission costs. Such small, but sophisticated, missions can be established as a series whose rate can vary in response to the establishment and requirements of Mission from Planet Earth. These missions will also stimulate immediate technology developments in such fields as robotics, artificial intelligence, and communications.

Mission from Planet Earth can begin in FY 1994 with Lunar Observer, followed by the initiation of MESUR in FY 1995. These missions, and their successors, can be done in a flexible manner to reflect the pace and character of the implementation of Mission from Planet Earth.

Pluto Flyby/Neptune Orbiter and Probe

Four American spacecraft have now made reconnaissance flybys of every outer planet except Pluto. In the 1990s, the detailed exploration of these worlds will begin with the Galileo orbiter/probe mission to Jupiter, and this will be followed by the Cassini orbiter/probe mission to Saturn.

Even these ambitious and exciting missions will leave two major gaps in our examination of the outer solar system: completing the reconnaissance of the whole solar system by sending a spacecraft mission to Pluto, and expanding the detailed exploration of the outer planets beyond the "gas giants" Jupiter and Saturn by sending orbiter/probe missions to the quite different "ice giant" worlds of Uranus and Neptune.

We plan to fill these gaps with a dual spacecraft mission: a Pluto Flyby and a Neptune Orbiter and Probe. Pluto is virtually an unknown and anomalous world, a tiny planet of rock and ice among huge gas-rich worlds. It has a tenuous atmosphere and an unusually large moon Charon, but its composition, landforms, and origin are unknown. Little more can be learned about Pluto from Earth; a spacecraft mission is needed to reveal this world and to complete a major goal: the reconnaissance by spacecraft of the entire solar system.

Neptune, recently but briefly revealed by the Voyager 2 encounter in 1989, is a strange "ice-giant" world, unlike the larger gas-giants Jupiter and Saturn. Neptune has a dynamic and violent atmosphere, a strongly tilted magnetic field, a complex system of rings and small moons, and a strange large moon Triton, which hosts erupting geysers.

The reconnaissance of Pluto and the exploration of Neptune will be done as a single, dual-spacecraft mission, taking advantage of the modular Mariner Mark II space-

craft and capitalizing on the inheritance from Cassini. We plan a new start on these missions for FY 1996, in order to maintain the momentum and technical skills produced by the Cassini development, and to be able to take advantage of rare Jupiter-swingby opportunities to reduce the travel time to Neptune and Pluto. A new start in FY 1996-1997 is required in order to reach Pluto before its methane atmosphere freezes onto the surface about the year 2020, not to reappear for over 200 years.

The Discovery Program

The Discovery Program is intended to achieve two important goals of planetary exploration: (1) to begin detailed and long-term explorations of the solar system's small bodies (asteroids and comets); and (2) to develop a series of scientifically exciting and cost-effective missions that can be carried out with small spacecraft, smaller launch vehicles, a constrained instrument payload, and highly focused science objectives.

Asteroids and comets have been little studied, despite their importance as records of solar system origins and as samples of the original material from which the planets were made. The first mission of the Discovery Program, a Near-Earth Asteroid Rendezvous (NEAR), will fill this gap by making a complete, long-term study of the nature, composition, and surface features of one of the group of asteroids that make close approaches to Earth.

NEAR, now under intensive study, can be started as early as FY 1994. Subsequent missions in the series, under consideration for starts in the later 1990s, include: (1) Earth-orbiting small-aperture planetary telescopes for long-term synoptic observations of solar system objects; (2) a Venus Atmospheric Probe to make definitive measurements of the chemical and isotopic composition of Venus' atmosphere; (3) a Mars Aeronomy Orbiter, to measure the thin upper atmosphere of Mars and its interactions with the solar wind; (4) a Lunar Aeronomy Orbiter, to measure the tenuous and dynamic haze of atomic particles around the Moon and their interactions with the lunar surface; and (5) a Phobos/Deimos Probe to determine the composition of the martian moons.

Toward Other Planetary Systems (TOPS)

For the first time in human history, we now have the technical abilities to attack the long-unanswered questions "Are we alone?" and "Are there planets around other stars?" In the 1990s, we plan to establish a long-term, evolutionary program (called TOPS) to search for, identify, and examine planets around other stars.

TOPS 0, the Reconnaissance phase of this effort, will start in FY 1993 as a combination of ground-based observations, scientific research, and technical developments. A major step will be support for the new Keck II telescope in Hawaii and

the subsequent use of both Keck telescopes (including dual operation as an optical interferometer) to examine nearby stars. Several years' observations with these two instruments could confirm (or deny) the existence of Jupiter-sized planets around stars within about 50 light-years of Earth.

The Exploration phase (TOPS 1) will involve the deployment of dedicated instruments in Earth orbit to begin higher-quality long-term observations of more distant stars. Current technical studies have identified three instrument concepts: the Astrometric Imaging Telescope, an Orbiting Stellar Interferometer, and the Precision Optical Interferometer in Space. These instruments could detect smaller (Uranus-sized) planets around a larger number of stars at greater distances from Earth. The ongoing TOPS 0 program will define these concepts in more detail to evaluate and select one as a new start mission, either as a free-flying spacecraft or attached to Space Station Freedom.

The Intensive Study phase (TOPS 2 and TOPS 3) involves the eventual construction and deployment of larger, second-generation instruments, either in Earth orbit (TOPS 2) or on the lunar surface (TOPS 3) as part of Mission from Planet Earth. Such instruments can observe even more distant stars and can detect even smaller (Earth-sized) planets around them. They can also make imaging and spectral measurements of any planets discovered, including the detection of specific atmospheric components (e.g., oxygen and methane) that could indicate the presence of life on these other worlds.

Technology Development

The planetary missions that we will start in the 1990s are possible only because of existing technology whose development was begun many years ago. But the more ambitious missions planned for the years immediately after 2000 — Mars surface rovers, sample return missions, Mercury orbiters, and advanced Earth-orbital observing facilities — cannot be done with the technology now at hand. An active program must be started to identify and develop critical technologies for these missions, so that the necessary technical capabilities will exist when they are needed.

To address this requirement, a cooperative effort is being established between the Solar System Exploration Division and NASA's Office of Aeronautics, Exploration and Technology. This joint program will identify and begin development of *enabling technologies*, which are essential to the missions; e.g., robotics, artificial intelligence, remote sampling equipment (including sample selection, collection, manipulation, and storage), and improved interplanetary transfer stages using solar- or nuclear-electric propulsion. A major emphasis will be the examination of *microtechnologies*, which can produce smaller, lighter, and more flexible rovers and sample return missions, with resulting savings in launch vehicle capabilities and costs.

This joint program will also study a range of *enhancing technologies*, which will make the missions more efficient, productive, and cost-effective. These include new analytical techniques, improved detectors for remote sensing, better spacecraft subsystems (computers, autonomous operation modes, and data storage), new capabilities in mission operations, and data management (especially for the large volumes of interdisciplinary data that these missions will return).

Many of the new technologies for planetary exploration in the next century are *generic technologies* that will be widely applied as "spinoffs" in other areas after their development has been forced by planetary mission requirements. This is especially true of developments in robotics, machine/human interaction techniques, and operation and data management techniques. Just as the Apollo Program produced major technical benefits for the nation, the technical needs for the next century of planetary exploration will drive our current technical abilities and will generate new and unexpected benefits in other areas of America's economy and public life.

Overview

1. Introduction

As the 1990s begin, America's planetary exploration program is again moving forward. Magellan, launched to Venus in May 1989, has already completed the initial radar mapping of Venus' cloud-shrouded surface, revealing unusual impact craters, gigantic frozen lava flows, and baffling structural patterns in the planet's crust.

The Galileo orbiter-probe spacecraft, launched in October 1989 on a wandering path that will reach Jupiter in 1995, has already made two planetary encounters: a flyby of Venus in February 1990 and an exciting close passage of Earth and the Moon last December. In addition to collecting environmental data about Earth, Galileo images of the Moon provided new views of the huge Orientale Basin and showed what may be an even larger impact basin near the Moon's south pole. Later this year, Galileo will make the first of two asteroid encounters, another historic moment for planetary exploration.

Mars Observer, scheduled for launch in September 1992, will provide a unique global scientific data base by measuring, over a full martian year, Mars' surface composition, atmospheric dynamics, volatile transport, gravity, and magnetic fields. With this information, we can probe in detail the planet's mysterious past history and climate, and we can make closer comparisons between the behavior of Mars and our own Earth.

Exploration of the outer solar system will soon enter a new phase with two major launches — the Cassini mission to Saturn in 1995 and the Comet Rendezvous Asteroid Flyby (CRAF) mission in 1996. CRAF will explore the solar

system's smallest and least known objects — asteroids and comets — by making a close flyby of an asteroid and then making long-term close-up observations of an active comet for nearly 3 years.

Cassini will extend the detailed exploration of the solar system's giant planets beyond Jupiter. From orbit, the spacecraft will observe Saturn's atmosphere, moons, and rings for several years. Cassini will also launch a probe to penetrate the thick, red, organic-rich atmosphere of Saturn's largest moon Titan and to discover the nature of Titan's hidden surface.

America is now planning a bold new thrust of planetary exploration. On July 20, 1989, President George Bush proposed a long-term program to establish a human outpost on the Moon and then proceed to the human exploration of Mars. Last December, the Advisory Committee on the Future of the U.S. Space Program endorsed this concept as "Mission from Planet Earth," a program of combined human and robotic exploration of the solar system.

The plans we make today will carry solar system exploration well into the next century along several different paths: initiating Mission from Planet Earth, exploring the most distant parts of the solar system, beginning exploratory studies of comets and asteroids, searching for planetary systems around other stars, and developing new technical capabilities to support these outward drives.

In addition to its traditional scientific goals, the planetary program now has a new and essential theme: *to prepare the way to the new frontier of the 21st Century.*

We will prepare for this new frontier by:

Exploring to the edge of the solar system.

Searching for planetary systems beyond our own.

Leading the way for human exploration of the Moon and Mars.

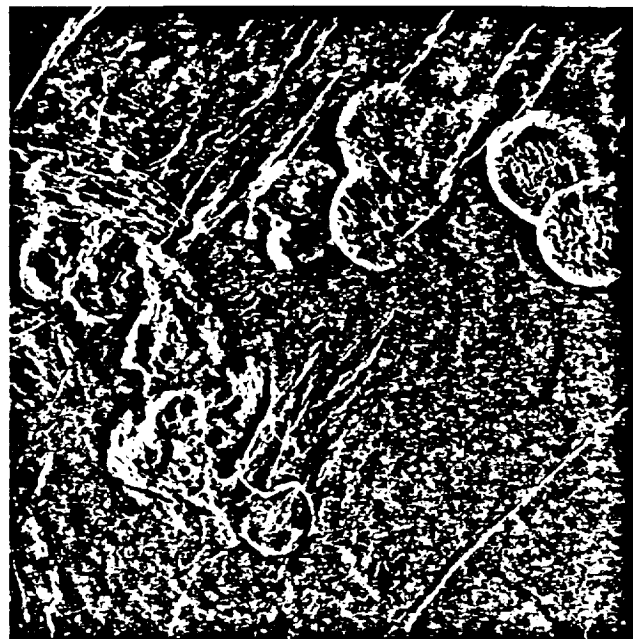


Figure 2. This area of Venus is approximately 200 km on a side. The view was acquired by the Magellan spacecraft with a synthetic aperture radar while mapping the planet from an orbital altitude of several hundred kilometers. Seen in the view are five large volcanic domes, roughly 30 km in diameter superposed on one another and about 1 km thick. Venus' geology is rich in unusual volcanic landforms.

1.1 Vision: Why we Explore the Planets

Seen as part of human history, planetary exploration is simply the most recent manifestation of our tendency to explore our surroundings. It embodies the same traits that have driven past explorations: curiosity, organized responses to challenge, risk-taking, and benefits obtained from discovery.



Figure 1. On December 8, 1990, Galileo swung past Earth and took this picture of the region Antarctica south of South America. The picture spans about 1,600 miles. The morning terminator is toward the right, and the South Pole is out of sight below the picture.

During the last two centuries, exploration and discovery have been particularly American themes. We see ourselves as a nation of explorers, a nation shaped by frontiers, both physical and intellectual, and by our responses to them. We do not wish to repeat the histories of earlier exploring nations — the 11th Century Vikings or 15th Century Portugal, for instance — who made great discoveries, then stopped and were swept aside by other exploring nations.

Planetary exploration is one highly visible way in which the American nation is defining itself. The planets are there: we explore them because we are Americans, who have always delighted in attempting what seemed impossible. To stop exploring the planets would be to lose part of this special identity and to trade part of our social and political system for something less clear and less energetic.

It has been said that our national drive consists of native human curiosity combined with a particular glory in exploration. It matters even more that, as a nation, we have always *believed* that this is the case. There are national personalities as well as individual ones, and, in both cases, personality can be the key to success and prosperity — or to their opposites. Seen in this light, planetary exploration is a shrewd investment in national self-realization, and the



Figure 3. Magellan acquired this view of Venus during its first mapping journey around the planet in orbit during 1990 and 1991. This region, roughly 1000 km on a side, shows a gigantic volcanic structure known as a corona. Such features are thought to be the result of hot rising bodies of magma which reach the crust and cause it to partially melt and collapse, generating volcanic flows and fault patterns that radiate from the central structure.

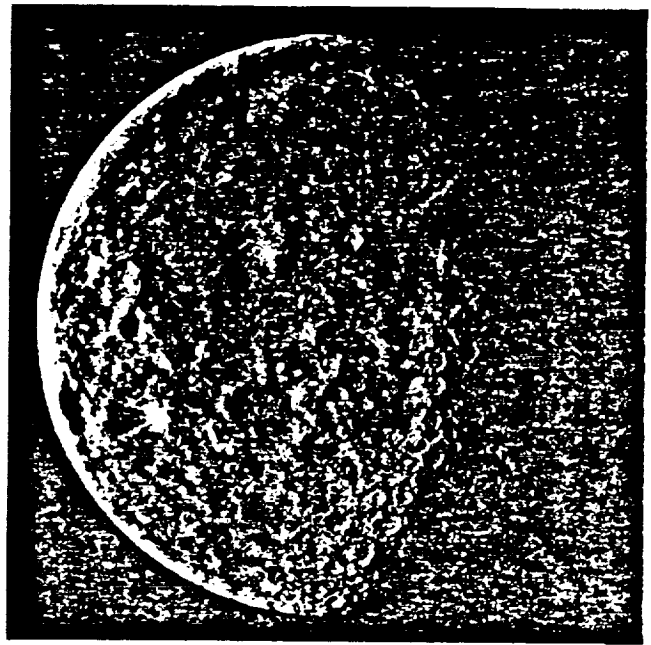


Figure 4. Galileo obtained this image of the Moon on December 8, 1990. It shows the dark Oceanus Procellarum in the upper center, with Mare Imbrium above it and the smaller, circular Mare Humorum below. The Orientale Basin, with a small mare in its center, is on the lower left near the limb.

planetary program is an important agent of positive national change.

In just a few years, planets that were tiny dots of light in the sky have been transformed into true worlds. Fantastic landscapes have unrolled before our eyes, finally answering questions thousands of years old, while at the same time providing the dreams for a new generation of explorers.

Closer to home, planetary exploration has provided all humanity with a global perspective on their social and environmental problems. The new view of Earth as a "Small Blue Marble" is best symbolized by the Apollo pictures of Earth in space, but that view has also been reinforced by the discovery that other "Earthlike" worlds have taken very different evolutionary roads, from the cloud-hidden hell of Venus to the frozen and nearly airless plains of Mars. The discovery that other planets can change — and have changed drastically — is a clear warning as we grapple with the changes that the human species is now producing in the atmosphere and oceans of our own world.

Before the planetary program, exploration had involved a few individuals going beyond familiar boundaries, with other people learning about it months or years later. In sharp contrast, the American planetary program has involved a whole *nation* going off into the impossible, while at the same time inviting the whole world to come

along. Thanks to organized technical capabilities and global communications, the whole world watched planetary exploration as it happened. A large public, which had already approved the program's efforts, could now feel that they had willed — and could actually *participate* in — the discovery of new worlds. Millions watched in real time as humans stepped onto the Moon. The Viking "weather reports from Mars" became routine additions to newspapers. Citizens saw pictures of Neptune on their TV screens literally moments after scientists received them.

Despite all we have accomplished, exciting challenges and huge unrealized benefits remain for the future. Unknown worlds wait to be discovered: the still-unseen half of Mercury and the whole surface of the most distant planet Pluto and its large moon, Charon. We are increasingly required to understand better the worlds we have already seen and to apply the information we obtain from them to understand our Earth. Future planetary exploration will continue to be a special activity for the human mind and spirit. The vision of tiny spacecraft, leaving Earth and heading for the unknown, is a symbol of all human exploration.

1.2 A New Era

The environment for planetary exploration has changed greatly in the last few years. The U.S.-U.S.S.R.



Figure 5. Galileo obtained this picture of the Earth on December 11, 1990, when the spacecraft was about 1.3 million miles away. South America is near the center, and the white, sunlit continent of Antarctica is below. Weather fronts are visible in the South Atlantic, lower right.

competition has disappeared, and has not yet been replaced by an equivalent driving commitment to cooperation in major planetary explorations. The simplest missions have been flown, the most accessible planets have been reached, and the most obvious discoveries have been made. The unanswered scientific questions are now more complex and challenging, and the missions needed to answer them have become more sophisticated and more costly. The growing Federal deficit — and the enormous concern it engenders — has undermined a once-strong national consensus that money spent in exploring space was an essential investment for the future. A growing public debate now asks why we explore space, why we should explore further, what benefits we obtain, and how we should structure our future explorations in terms of both national philosophy and program details.

Our national character and our willingness to make present sacrifices for future benefits are being severely tested. Are we still a nation of explorers? Can the American people and their institutions still respond to the challenges that the solar system provides?

Clearly, we *can* continue to explore the planets. In some ways, we can plan more confidently for the planetary missions of the 2000s than we could for the missions of the 1960s. The resources, achievements, and experience accumulated over 30 years make it possible to plan clearly the exciting explorations of the next century. These qualities allow us to look ahead with confidence; *we know how to go about exploring the planets.*

Circumstances challenge us to judiciously select a program of future missions to maintain the vigor and momentum of planetary exploration. The FY 1991 Deficit Reduction Agreement between the Administration and the Congress established Federal spending limits for the next 5 years. A growth target for NASA of 6 to 8% per year has been mandated. Congressional sensitivity to reprecings and cost control is heightened in the context of other major budget difficulties. In addition, the future direction of Mission from Planet Earth is uncertain; it is strongly supported by the Administration, yet deferred by the Congress.

All implications point to a conservative approach to near-term planning, with a focus on small missions, the research base, and scientific data analysis. Yet we must continue to move forward in planetary exploration. Our 10-year strategy strives to balance the need for progress with existing fiscal constraints, and it emphasizes cost-effective, incremental approaches to realizing that progress.

1.3 Strategic Planning Approach

Our understanding of the origin and evolution of the solar system is maturing through a classic interactive process involving basic research and exploration flight pro-

grams. At the heart of this process is a strong research program involving theoretical studies and analysis, laboratory investigations, and ground-based planetary astronomy. These research activities not only fit the known pieces of the solar system puzzle together, but also provide the insight for new directions of inquiry to find new pieces as the puzzle grows. This knowledge drives the exploration flight program, which in turn will bring the new pieces to the puzzle-building process. The data returned from each planetary mission recharge our basic research effort to understand our origins, bringing the answers, which beget new questions.

The effectiveness with which the exploration flight programs (and other related activities) succeed in executing the paths of inquiry developed by the basic research activities is critically dependent upon our strategic planning efforts. Strategic planning is the process by which we define the scope of solar system exploration and determine objective priorities within this scope. Determining priorities means maintaining an effective balance between the compelling goals of solar system exploration and the constraints of program budgets, technical capabilities, and celestial mechanics. Strategic planning is an ongoing activity that continually adjusts and builds our flight program plans in response to the emerging knowledge of research and analysis efforts, and the dynamics of the programmatic environment within which we function. Never has the challenge of effective strategic planning been more daunting than it is today: our better understanding of solar system origin and evolution is fostering a growing appetite for new knowledge at the same time that our space program must compete for dramatically shrinking discretionary funds within the Federal budget.

The Solar System Exploration Division has engaged in strategic planning almost since its creation. The process has matured significantly over the years, becoming increasingly interactive with other organizational elements of NASA, the NASA Advisory Council, and the Space Studies Board of the National Academy of Sciences. Perhaps the most important factor in the planning process is an established priority of scientific objectives for solar system exploration. Such priorities continue to be effectively provided to our planning activities by the Committee on Planetary and Lunar Exploration of the Space Studies Board and the Board itself. Today, solar system exploration strategic planning is conducted with considerable support from the Solar System Exploration Subcommittee (SSES) of the Space Science and Applications Advisory Committee (SSAAC), a committee of the NASA Advisory Council with oversight responsibility for NASA's Office of Space Science and Applications.

In 1988, the Office of Space Science and Applications (OSSA) established a process to develop and update a Strategic Plan for all of its activities, including solar system exploration. The OSSA plan, and the advisory process that underlies it, provides decision rules for selecting candidate missions and establishing priorities for their development. First, the Plan defines a group of possible missions as Major, Moderate, and Small on the basis of scientific scope (and resulting cost). From this group, a priority list of missions covering all OSSA disciplines is established for funding during the next few years by evaluating scientific importance, technical readiness, cost, and outside factors such as available funds. To ensure that the plan remains current and flexible, OSSA and its advisory committee evaluate it yearly, and a new mission queue is established every 3 years.

The OSSA Strategic Plan provides, at any moment, a view of long-term priorities and decisions for all the OSSA disciplines. By establishing a firm queue of candidate missions, the Plan eliminates annual competitions between OSSA divisions for the next "new start." The periodic revisions of the Plan make it adaptable to changing political and budgetary climates, a factor that is especially important in this period of constrained space budgets.

The current cycle of OSSA strategic planning will refresh the queue of programmatic new starts. In preparation for this summer's triennial SSAAC Workshop, the SSES held its own strategic planning workshop in February 1991 to review and update the Solar System Exploration Division Strategic Plan for the year period FY 1994 to FY 2003. The strategic plan that emerged from this workshop and subsequent refinement efforts is the subject of this document. It is a plan of preparation for the bold frontiers of space to be explored in the 21st Century. It is also a plan of limits, carefully crafted to fit within the near-term programmatic constraints apparent to us all. In the sections that follow, we first lay out the rationale and implications of our strategy, and then present the specific recommendations that flow from this strategy.

2. The Solar System Exploration Program Today

2.1 Program Goals

The goals of the solar system exploration program are:

- **Solar System Origins:** Understand the process of solar system formation, in particular planetary formation, and the physical and chemical evolution of protoplanetary systems.
- **Planetary Evolution and State:** Obtain an in-depth understanding of the planetary bodies in our solar system and their evolution over the age of the solar system.
- **Evidence of Life:** Search for the evidence of life in our own and other solar systems, and understand the origin and evolution of life on Earth and other planets.

More similar to Earth, but still very different, are Venus and Mars. On these planets, the records of early planetary history have been overprinted (and sometimes totally destroyed) by the products of more recent geological change: crustal movements, younger volcanoes, deep canyons, atmospheres, water, ice, and surface erosion. At the far end of this spectrum of worlds is Earth, with its continuing volcanism, earthquakes, and mountain-building, its oceans, its atmosphere, and the unique presence of life.

Scientific questions about the inner solar system concern both planetary origins and planetary evolution: "Why do planetary bodies so nearby, such as Earth and the Moon, form with such different properties?" and "How and why do initially similar planets, such as Earth and Venus, change and become so different?"

Understanding how and why the terrestrial planets change is important for one simple reason: we live on one. Studies of other worlds have made us aware of the fragility of the life-supporting parts of any planet — the *biosphere*, containing the atmosphere, oceans, and land surface — and how drastically they can change. Venus may once have had oceans before the buildup of carbon dioxide in the atmosphere started a "runaway greenhouse effect" that boiled off the water, and with it, all chances for life. Mars may once have had a thick atmosphere, with floods of water pouring down huge channels; now it is cold and dry. Earth is a planet, too, and humans are changing it just by being here. The scientific understanding of planetary change has a new urgency because of concerns about the future of our planet and of the civilization that depends on it for survival.

To understand how terrestrial planets change, we need missions more ambitious and capable than any we have flown — long-lived and sophisticated orbiters, surface stations, and independent roving vehicles. These missions are essential to provide detailed and global scientific characterizations. Finally — and this is the lesson from the Apollo Program — we need returned samples, so that the full resources of terrestrial laboratories can be applied to determining the mineral composition, chemistry, physical properties, and detailed geological histories of the worlds we study.

Mission from Planet Earth provides a new context for the scientific exploration of the Moon and Mars, but the continued exploration of Mercury and Venus also remains an important goal for solar system exploration. Mercury, deep in the Sun's gravity well, is hard to reach with available propulsion. The broiling surface of Venus, with its overlying weight of steamy and opaque atmosphere, makes close-up exploration of this planet difficult — and in some cases, impossible — with our current technology. For these reasons, missions to explore these worlds will not be initiated for several years.



Figure 6. Mariner 10 acquired this view of Venus during its tour of the inner solar system. Venus' thick atmosphere is composed largely of carbon dioxide with sulfuric acid clouds. At high altitudes, winds in the atmosphere blow several hundred meters per second to the west encircling the planet in only 4 days.

However, we know enough about both Mercury and Venus to plan the next missions in some detail. For Mercury, a planet with half its surface still unseen, the next step should be an orbiting spacecraft to map its whole surface, determine its chemical and mineral composition, and measure its gravitational and magnetic fields; in short, to characterize Mercury as a total world and to be able to compare it with the Moon, Earth, and Mars. Close to the Sun, and deep within the Sun's gravity field, Mercury provides an exciting target for many different scientific investigations: the close-in solar environment, the particles and fields expelled from the Sun, even the fundamental nature of gravity and tests of Einstein's Theory of Relativity under extreme conditions. For these reasons, a Mercury Orbiter mission could be supported by other OSSA science Divisions as well.

We do not yet have the technical ability to place complex or long-lived missions on the intensely hot surface of Venus, but we can expand exploration of the planet by probing its atmosphere. Previous atmospheric measurements by both U.S. and U.S.S.R. probes have left undetermined the nature and distribution of the tiny amount of water vapor present in the crushing weight of carbon dioxide, and the abundances and isotopic compositions of noble gases that can provide keys to Venus' origin and history. A more sophisticated atmospheric probe of Venus, able to make better measurements with more advanced instru-

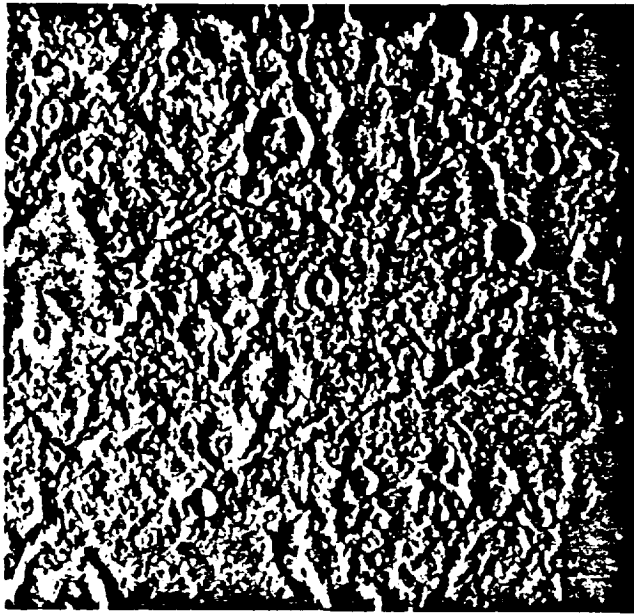


Figure 7. This Mariner 10 image of Mercury shows a region of the planet termed "weird terrain." This region is at the antipodal point to the large Caloris Basin. Perhaps the shock wave of the impact that produced the Caloris Basin was focused in this region, jumbling the crust into a maze of complex blocks. The area shown is about 100 km on a side.

ments, would be a major step forward in our efforts to understand why the planet once called "Earth's Twin" is now hellishly different from Earth. Such a probe mission might be done within the planned Discovery Program.

2.2.2 Mission From Planet Earth: Robots and Humans in Concert

Of all the planets, moons, and small bodies in the solar system, only two — the Moon and Mars — are being seriously considered as destinations for the next generation of human explorers. From the Apollo Program, we understand how to get humans to the Moon and how they can work for at least short periods on its surface. Mars is more distant and more Earth-like, harder to get to and less explored, but intriguing both scientifically and culturally.

The Moon, we have learned, is an important world for two reasons. First, it is a museum of preserved early planetary history. Its ancient cratered landscapes contain the oldest planetary rock samples yet found. From the returned Apollo samples, we have deciphered an early lunar history characterized by huge meteorite bombardments, moonwide melting, and prolonged eruptions of giant lava flows. Then 3 billion years of relative quiet followed. The Moon and its rocks retain a record of planetary origin and early development that has been destroyed on the geologically active Earth; if we wish to search for the "roots" of our own world, we must search on the Moon.

Second, the Moon's airless surface has trapped the charged atoms and particles emitted from the Sun and the stars. Because the lunar surface is so old and changes so slowly, it contains a record of the Sun's history that may extend back billions of years. By analyzing lunar surface samples, we can construct the life history of our own local star, determine its past in more detail, and speak more confidently about its future.

Despite the tremendous successes of the Apollo Program, we have not even explored the entire Moon. The Apollo landings and sample collections were limited to about 5 percent of the Moon's surface. The chemical composition of about 80 percent of the Moon's surface — and whatever future resources those regions may contain — is unknown. No samples have been collected from the lunar poles, the lunar farside, large lunar impact craters, or sites of possibly young lunar volcanic rocks. The magnetic field of the Moon is not well determined, we do not have good maps for the strange magnetic anomalies that exist in the upper lunar crust, and we have not yet been able to determine whether or not the Moon has a metallic core. The Moon's gravity field, although sufficiently measured to show large anomalies like the *mascons*, is not precisely known. We cannot yet determine the details of the Moon's internal structure or — for that matter — accurately plan for future human or robotic landings over most of the Moon. Details of the Moon's later geologic history (and the existence of young volcanic eruptions) have not been settled. The much-debated question about the existence of water at the lunar poles is still unanswered; the answer is important to lunar science, but even more important to future human habitation of the Moon.

Mars is a very different world, partly ancient, partly modern. It stands somewhere between Earth and the Moon in the series of planetary evolution. Its heavily cratered southern hemisphere also preserves the record of ancient bombardment seen on the Moon. But elsewhere, Mars shows the results of more recent, and more Earthlike, processes: volcanic mountains, canyons, winding flood channels, polar caps, clouds, and wind-formed sand dunes.

Mars is more complex and active than the Moon, but we know less about it. We have no returned samples, only two Viking Lander surface analyses, which provide a crude idea of the planet's composition and history. We have no long-term data on the dynamics and composition of Mars' atmosphere and how it changes with the passage of the martian seasons. We do not know where most of the water on Mars is located or how it migrates between atmosphere, polar caps, and soil. We have no data on the martian interior, whether it has a crust and mantle, whether there are earthquakes, what the planet's magnetic field is like, and the size of any metal core. We have recognized, but not

solved, the mystery of Mars' past climate: why it appears to have been warmer and wetter in the past. Despite the best efforts of Viking, we have not settled the age-old question about whether there is life — living or fossil — on Mars.

Some of these problems will be solved by data returned by the Mars Observer, which will be launched to Mars in 1992 to make detailed observations of the planet's surface composition, atmospheric characteristics, and magnetic and gravity fields over a full martian year. This information will help us to understand Mars better as a dynamic planet. But to fully understand Mars, and to prepare for human landings, we must send other, more sophisticated missions. We must explore the martian surface fully with long-lived landed instrument networks and with roving vehicles. We must characterize the martian atmosphere and its behavior in more detail. We must finally collect samples of Mars and return them to Earth for analysis, to determine the nature and history of the planet and to make a more extensive search for evidence of life.

Decisions about when humans will return to the Moon and travel to Mars have still to be made. In the meantime, plans for the future exploration of these worlds will go forward with a dual purpose: *to carry out exciting scientific explorations of the Moon and Mars that will, at the same time, pro-*

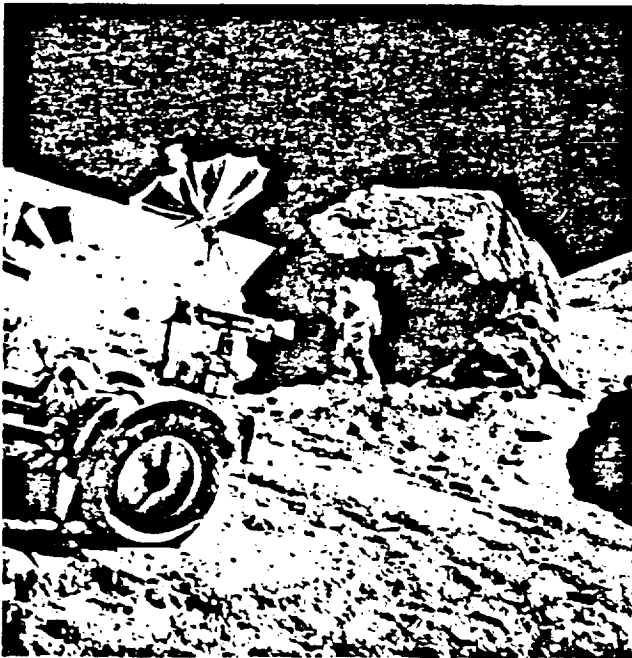


Figure 8. Geologist Harrison "Jack" Schmitt gathers samples from "Split Rock" in the lunar highland surrounding Mare Serenitatis. Schmitt was a member of the Apollo 17 mission to Taurus Littrow that landed on the Moon in December 1972. As a geologist working in situ, Schmitt was able to make significant contributions to this mission. He conducted the planned traverses to known targets like "Split Rock" and made serendipitous discoveries, such as the "orange soil" also found in the area.



Figure 9. This Viking Orbiter mosaic shows the south polar cap of Mars near its final stages of retreat near the end of southern summer. The temperature of this cap is controlled by carbon dioxide ice keeping it at a temperature near 130 K throughout the martian year. The cap is approximately 500 km in diameter.

vide the information needed to plan the subsequent human exploration of these worlds.

These two purposes support each other, for the information needed to answer critical scientific questions about the Moon and Mars is equally essential to plan their exploration by human beings, especially: (1) high-resolution imagery of surface features; (2) the physical and chemical nature of surface materials; (3) the nature, location, and behavior of water and other volatile compounds; (4) the nature and intensity of radiation at the surface; (5) (for Mars) the composition and dynamics of the atmosphere, including wind, dust, and weather patterns; (6) (for Mars) the nature of organic materials in the surface and the presence or absence of life.

The next logical step in lunar exploration is Lunar Observer; for Mars, it is a global network of landed instruments. These two missions are discussed further in Section 3.2.1 and in detail in Volume II of this series.

Beyond a Mars global network, plans for robotic exploration of Mars remain incomplete and challenging. Answering the questions we have outlined requires larger regions of the martian surface to be explored by rovers. Eventually, samples must be collected and returned to Earth. Because Mars is a complex and diverse planet, several rovers and sample return missions will be needed in order to understand Mars well enough to plan its human exploration. The Solar System Exploration Division is now studying how a series of such missions might be done in a steady, cost-constrained, evolutionary manner. Strongly indicated is the use of new "microtechnologies" to produce small, "smart" rovers and sample-collection devices that would not need large and expensive launch vehicles to carry them to Mars. The number and pace of such missions could be adjusted to fit the funding available in the years ahead, consistent with the "go as you pay" philosophy advocated by the Advisory Committee on the Future of the U.S. Space Program. These missions would then lead to the realization of the ultimate goal of Mission from Planet Earth: a journey into tomorrow — a human mission to Mars.

2.2.3 Small Wonders: The Secrets of Comets and Asteroids

The most abundant objects in the solar system are the smallest. Thousands of asteroids, ranging from a few tens of meters to hundreds of kilometers in size, swarm in the Asteroid Belt between Mars and Jupiter. Dozens, perhaps hundreds, range inward through the solar system, crossing the orbit of Earth and even approaching the Sun. Hundreds of comets move in long elliptical orbits about the Sun. Billions of comets may dwell in the interstellar darkness far beyond Pluto, waiting for the gravitational tug of a passing star to send them plunging down toward the Sun.

Comets formed in the freezing regions of the solar system far from the Sun. Their original characteristics — chemistry, mineral composition, physical properties — were more typical of the solar nebula at the time the Sun and planets formed. Most comets have remained far from the Sun ever since, in regions so cold that their characteristics have not been changed by solar heating. Comets, especially their hidden interiors, may be the most primordial and unchanged material now available in the whole solar system.

Asteroids are a more varied group of bodies, if we judge from the meteorites (believed to originate in the asteroid belt) that fall to Earth to be studied. Some meteorites, and the asteroids from which they came, appear primordial and are composed of water-rich minerals and organic compounds that formed at low temperatures. Other meteorites, even those that preserve ages as old as the solar system itself, show modifications: melting, chemical processing, and the collisional shattering and mixing of different materials on the surfaces of their parent bodies. Clearly, the study of

both of these families of small bodies will reveal much about the origin and early evolution of our solar system.

Another reason for taking closer and longer looks at comets and asteroids is to understand the role that these small bodies may have played in the origin of planets, including Earth and the life on it. Were the small objects that came together to build up Earth like the present population of asteroids and comets? Was the water that makes Earth "the water planet" produced with the Earth as it formed in the hot part of the inner solar nebula, or was the water brought in from colder regions as part of a late bombardment by asteroids and comets?

Could comets and primitive asteroids have brought in more than water? Did organic chemicals, the "building blocks" that eventually made up the life-forms of Earth, develop within the crust of the primitive Earth, or were they too brought in by late-striking comets or asteroids? A whole class of meteorites (and their parent asteroids) are rich in complex organic compounds, including the biologically critical amino acids. The recent spacecraft flybys of Halley's Comet showed that organic molecules are present in its coma and tail, and the unexpectedly dark color of the comet's nucleus is apparently produced by dark carbon-rich compounds. Ground-based observations of more distant comets also suggest that organic compounds are present in many of them. But whether such materials were important to the development of life on Earth is not clear. We must visit these objects to find the answers.

A more recent, and sobering, possibility is that comets and asteroids have destroyed life on Earth as well as helping to create it. Occasionally, asteroids and comets pass through the inner solar system, often crossing the Earth's orbit in their travels, and when they do, there is a slight chance that they will collide with Earth. Such catastrophes have occurred in fairly recent geological time. One of the most exciting scientific developments of the last decade has been the increasing recognition that the impact of an extraterres-

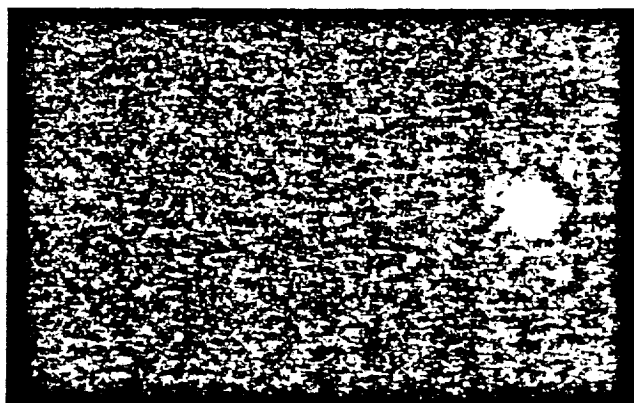


Figure 10. Comet Halley on January 20, 1986. (Courtesy of U. Fink)

trial object about 10 km across, either a small asteroid or the nucleus of a comet, caused the major biological extinction that took place at the end of the Cretaceous Era 65 million years ago. This event was a turning point in Earth's biological evolution — and in our own. The formidable and long-established dinosaurs were extinguished, together with about 75 percent of other (but lesser-known) species at that time. Fortunately for our own origins, some primitive mammals survived to produce more specialized descendants, including us. The comets and asteroids that we explore today are a reminder that the influence of the solar system on the Earth and its inhabitants may have been substantial in the past — and could be just as significant in the future.

Despite their scientific importance, comets and asteroids have been bypassed in the outward march of planetary exploration. The first spacecraft flyby of a comet was not made until 1985, when the U.S. International Cometary Explorer encountered Comet Giacobini-Zinner. The following year, a major international effort, the "Halley Armada" of spacecraft from Japan, the U.S.S.R., and the European Space Agency swept past Halley's Comet and studied it at close range. Images of the comet showed a dark, misshapen nucleus, more than 14 km long, as well as jets of gas erupting from beneath its surface as the Sun warmed it. Other spacecraft instruments studied the comet's chemistry, measured its magnetic field, and detected large amounts of organic molecules boiling off its surface.

These flybys set the stage for the more ambitious Comet Rendezvous Asteroid Flyby (CRAF) mission to be launched in 1996. CRAF will fly in formation with an active comet for several years to measure its composition and properties and to record the changes in the comet's activity as it sweeps by the Sun and back to the cold outer solar system again.

Asteroids have been even less studied than comets. No asteroid has yet been visited by a spacecraft, and our current images of asteroids are little better than they were at the beginning of the Space Age. This situation will change in October 1991, when the Galileo spacecraft, outward bound to Jupiter, makes the first flyby of one of these mysterious objects, a small asteroid called Gaspra. Later, as Galileo swings past the Earth and out again, it may fly by another asteroid, Ida, in August 1993. In the late 1990s, both the CRAF and Cassini missions will fly past other asteroids on their outward paths, as will subsequent missions to the outer solar system.

In one respect, asteroids are just like larger planets and comets: quick flybys, no matter how many, cannot provide all the information we need. To explore asteroids adequately, we need more capable missions, especially missions that can rendezvous with asteroids and examine them over long periods of time. This is not a simple task. The Asteroid Belt is not easy to reach in terms of time or

propulsion. Rendezvous missions, whether for one asteroid or many, need large, capable spacecraft and correspondingly large, capable launch vehicles. In addition, ground-based studies have demonstrated that there are many kinds of asteroids — metal-rich, silicate-rich, carbon-rich, and still-undetermined types. No one encounter with a single asteroid is enough to understand the whole population; in the long run, multiple rendezvous encounters with different asteroids must be performed.

Planning to explore asteroids is therefore going forward on two levels. First, we can take advantage of the fact that some asteroids are not far away; a group of near-Earth asteroids have orbits that regularly bring them close (although not dangerously close) to Earth. Some of these asteroids are easier to reach from Earth than the Moon is. These near-Earth asteroids can be reached, for both flyby and rendezvous missions, by small, relatively simple spacecraft that can still carry enough instruments to make the first detailed explorations of an asteroid.

The study of near-Earth asteroids (and possibly near-Earth comets) is such an important goal that it has become the cornerstone of a new effort in planetary exploration, the Discovery Program (see Volume IV). Earlier studies identified a Near-Earth Asteroid Rendezvous (NEAR) as an excellent candidate for a Discovery mission, and this mission is now being actively planned.

The second, more ambitious stage of asteroid exploration is to study asteroids where most of them live — in the Asteroid Belt beyond Mars. Such distant and long-term explorations are not possible with the small spacecraft and constrained resources of the Discovery Program. Studies are already under way to define more capable missions to reach the Asteroid Belt and make long-term observations of numerous asteroids. One such mission would be a Multiple Mainbelt Asteroid Rendezvous, a spacecraft which could move through the Asteroid Belt to study several different kinds of asteroids in turn.

Still more ambitious, and more rewarding scientifically, will be missions that achieve the ultimate goal of comet and asteroid exploration — the return of actual samples to Earth, where they can be studied with the full array of human scientific capabilities. Only sample returns can reveal the critical characteristics of these bodies — chemistry, mineral composition, ages, histories, and the effects of the Sun and the space environment upon them during the past several billion years. Only with sample returns can we obtain and analyze the primordial dust and ice in comets, search for actual grains of interstellar matter in them, and understand the diversity that we see only dimly among different asteroids.

Mission studies indicate that a Comet Nucleus Sample Return Mission can be done with the same Mariner Mark II spacecraft now being developed for other outer solar sys-

tem missions. The spacecraft could also be modified to return asteroid samples, producing a tremendous scientific bonanza from a relatively small investment in additional technology and spacecraft capabilities.

2.2.4 The Outer Solar System: A Search for Beginnings

The outer solar system beyond the Asteroid Belt contains five of the nine known planets, which together add up to 99 percent of the mass in the solar system, excluding the Sun. Four of them — Jupiter, Saturn, Uranus, and Neptune — are huge worlds: two of whirling gas, two of ice and rock. The fifth is the tiny, anomalous planet Pluto, so far away that it has never even been reached by spacecraft.

Except Pluto, the outer planets are giant globes 50 to 1,000 times the volume of Earth. Their solid surfaces, if any, are buried far beneath huge, colorful atmospheres that display circulation bands and storm patterns on an enormous scale. Strong magnetic fields reach out from these planets into space, creating zones of trapped radiation that are larger and more intense than anything seen elsewhere in the solar system. All these giant worlds are surrounded by rings made up of uncountable small particles; these rings vary from the thin, nearly invisible ones around Jupiter, Uranus, and Neptune to the extensive array that surrounds Saturn.

The outer planets are surrounded by numerous moons. These satellites, some of them as large as the planet Mercury, constitute more than 50 new worlds, and they vary lit-

erally between fire and ice. From the erupting volcanoes of Io to the contorted icy landscapes of Miranda, and from the ancient airless surface of icy Callisto to the thick organic-rich atmosphere of Titan, each presents excitement, unanswered questions, and challenges for the future.

Our probing of the dark, cold regions of the outer solar system is driven by special questions concerning our own origins. How did the solar system form? What were the physical and chemical conditions in which planets could develop? What were the primordial planets like?

Our theories and explorations so far indicate that the Sun and planets formed together by the collapse of a huge cloud of whirling dust and gas — the *solar nebula*. But we still do not know the details of the collapse process, the exact steps by which the dust and gas accumulated into planets, what the Earth and other terrestrial planets were like at the beginning, and what the Sun was like when it first began to burn nuclear fuels.

If we wish to find our planetary roots, the outer solar system is perhaps the best place to start. At the beginning, temperatures in the outer solar system were below 200 K, and even volatile gases solidified to ice or were trapped as dense atmospheres around growing solid planetary cores. The atmospheres of the outer planets, composed chiefly of hydrogen and helium, are similar to the present composition of the Sun and the inferred composition of the original solar nebula. Many small objects — moons, asteroids, and comets — seem to be made of original mixtures of ice and rock, too small to generate the high-temperature geological processes that have reshaped the inner planets.

However, searching for such original records in the outer solar system will not be easy. It is now clear that most of the outer solar system is not a frozen exhibit that has remained unchanged since it formed. Even our initial explorations of this region have shown us that change and evolution are going on. The colors in the atmospheres of Jupiter and Titan show that atmospheric development and chemical processing are occurring as we watch. Smaller worlds show a surprising range of geological activity, including sulfur-fueled volcanoes on Io; bizarre geological deformation in the icy crusts of such moons as Europa, Enceladus, and Miranda; and erupting geysers on Neptune's icy moon Triton.

Despite the existence of change in the outer solar system, the records of our planetary origins may still be preserved there in a few places: (1) in primitive, unheated comets, which may harbor samples of original nebular dust and ice; (2) in the atmospheres of the gas-giant planets, whose gravity fields are strong enough to retain all the original gases and preserve the original bulk composition despite later atmospheric change; (3) in the thick, red-brown atmosphere of Titan, Saturn's largest moon, where the original organic chemistry that led to life elsewhere may still be

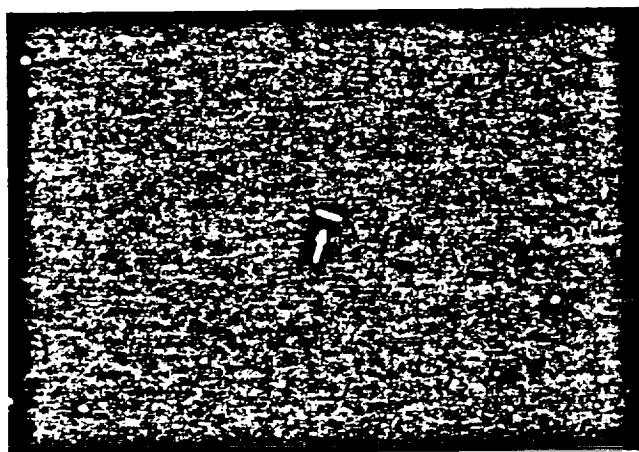


Figure 11. The discovery image of Chiron. For years after its discovery in 1977, Chiron was thought to be a member of a new population of asteroids orbiting between Saturn and Uranus. In 1988, it was observed to brighten more rapidly than expected for an asteroidal body approaching the Sun, and subsequent CCD images revealed the presence of a comet-like dust coma surrounding the object. Recently, the report of a CN coma has strengthened the designation of Chiron as a comet. Thus, Chiron may provide a crucial link between asteroids and comets and lead to a better understanding of the formation scenarios for these small bodies in the early solar system. (Courtesy of C. Kowal)



Figure 12. This Voyager image of Jupiter shows belts (dark) and zones (light) that move relative to one another in east and west directions with velocities of hundreds of meter a second.

trapped and frozen for our inspection, and (4) in Pluto, which may be a relic planetesimal from the accumulation era of the giant planets.

The outer planets also exhibit many physical processes, including magnetic fields, complex rings, atmospheric storms, and radiation belts. These features appear at intensities and on scales that we could never observe on or around the Earth. The outer planets thus provide us a laboratory to understand how fundamental physical processes operate under different conditions in planetary systems.

Within the next few years, missions now under way or in development will begin the detailed exploration of the outer solar system. The Galileo orbiter/probe to Jupiter will provide our first long-term, close-up view of the entire system of a giant planet: details of its atmospheric composition and the swirling storms that churn it; measurements of its intense magnetic fields and radiation belts; and detailed maps of its different moons. A few years later, Cassini will begin similar explorations of Saturn, and will explore the prebiotic origins of life by sending a probe into the thick organic-rich atmosphere of Saturn's deep-frozen moon Titan.

However, two major gaps will remain in our study of the outer solar system: completing the reconnaissance of the solar system by exploring distant and yet-unvisited Pluto, and beginning the exploration of the smaller "giant" planets, Uranus and Neptune, that lie beyond Saturn. We propose to close both gaps at once with a single dual-space-

craft mission: a flyby of Pluto, and an orbiter-probe to carry out a long-term study of Neptune.

Unlike the gas- and ice-giant worlds of the outer solar system, Pluto is a tiny ball of ice and rock, in some respects much more like an outer-planet satellite than a planet in its own right. Pluto and its large moon Charon are a binary planet system. Recent ground-based observations of Pluto show that it has a variegated surface, with bright regions of ice and darker regions that could be exposed bare rocks or dark organic material. Pluto also has a thin atmosphere, composed chiefly of methane. This atmosphere springs from its frozen surface only during the warmest few decades of Pluto's 248-year journey around the Sun, including the current several decades surrounding Pluto's perihelion in 1989.

Beyond these few facts, Pluto is unknown. Without the close look provided by a spacecraft, we cannot reveal Pluto's landscapes or determine its composition, density, atmospheric characteristics, and geological history. What does Pluto look like? What is it made of? Exactly what other gases does its atmosphere contain, and how does this atmosphere wax and wane as Pluto circles the Sun? Is Pluto a twin of Neptune's strange icy moon Triton, is it like the icy moons of Jupiter and Saturn, or is it something totally different? How did Pluto come to inhabit the realm of giant gas planets like Jupiter and Neptune? How and when did Pluto acquire a moon of its own?

Uranus and Neptune are also special planets. They are both ice giants, different from the huge gas giants Jupiter and Saturn. They are smaller, each less than a tenth of Jupiter's volume. Their atmospheres are bland and greenish in appearance, and their bulk is made of ice and rock. Despite their

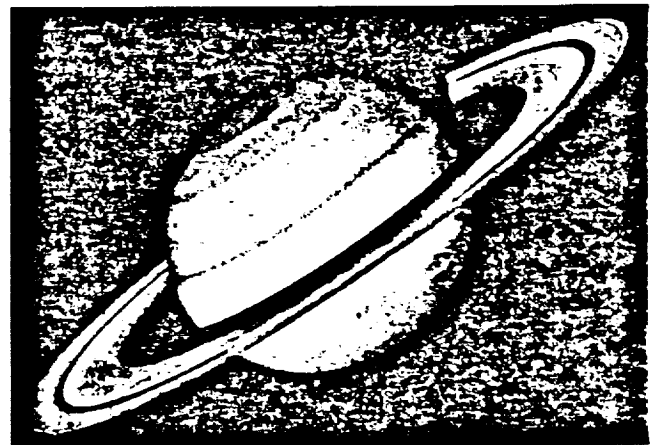


Figure 13. Voyager acquired this view of Saturn and three of its satellites while approaching the ringed planet. The disk of Saturn casts a shadow across the rings. The satellites Mimas, Enceladus, and Tethys seen in the lower right all orbit Saturn in the plane of its rings and its equator.

distance from the Sun, their atmospheres are highly active. Neptune's wind speeds, recorded by Voyager 2, are the highest observed anywhere in the solar system. This may in part result from Neptune's strong internal heat source.

The Voyager 2 flybys transformed Uranus and Neptune from tiny blobs of light in telescopes into awesome and dynamic worlds, but even Voyager 2 provided only brief snapshots. We do not know how these planets behave over longer periods of time. To find out, we must move from the reconnaissance of Voyager 2 into long-term exploration. Just as the Galileo orbiter/probe mission followed the Pioneer and Voyager flybys at Jupiter, the next steps for Uranus and Neptune are similar orbiter/probe spacecraft that can make long-term observations of the planets and directly analyze their strange atmospheres.

Our long-range planning studies have also already begun to consider the next exploration step at Jupiter after Galileo. Given successful achievement of the Galileo mission objectives, we will be ready to undertake intensive studies of the

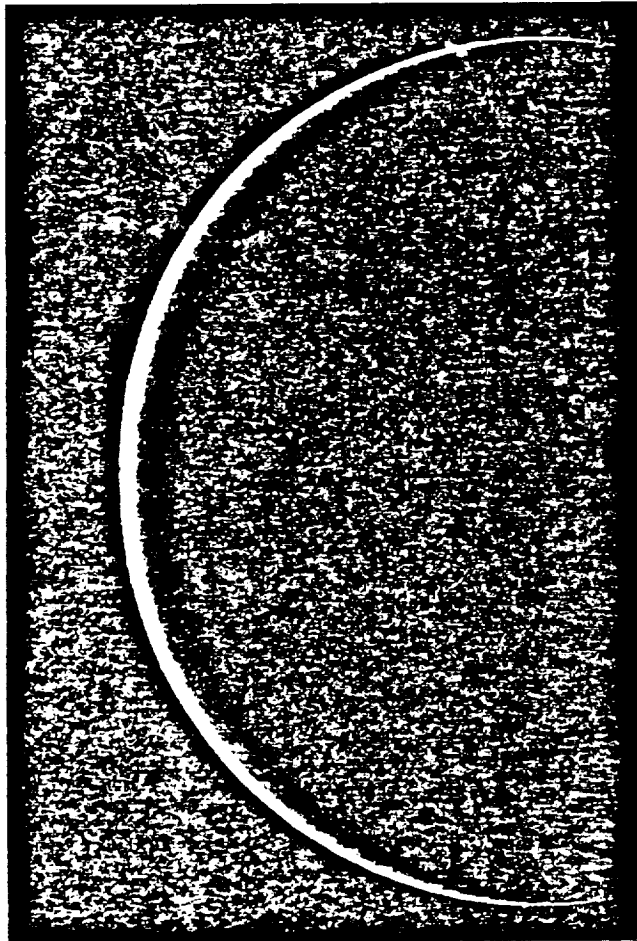


Figure 14. Voyager 2 acquired this view of Uranus in late January of 1986 as it departed the Uranian system on the three and a half year trip to Neptune. Uranus' atmosphere contains methane and high altitude photochemical smog, which absorb red light and give the planet a greenish color.

Jovian system. For this initiative, a Jupiter Grand Tour project has been proposed, including two elements: (1) a polar fields and particles orbiter to map the inner Jovian magnetosphere, and (2) an equatorial probe carrier to deploy landers at several of the Galilean satellites and a deep entry probe into Jupiter's atmosphere. Follow-on Cassini objectives are also beginning to be contemplated for Saturn.

The outer solar system is one region where American leadership in space exploration has been unchallenged. Only American spacecraft have visited these outer worlds, and other American spacecraft are ready to follow them. Even now, Voyager 2 results and ongoing Earth-based observations tantalize us with unsuspected discoveries, and new knowledge. We can maintain visible national leadership here, and at the same time push the frontiers of scientific discovery farther than ever before.

2.2.5 Beyond Pluto: The Search for Other Solar Systems

The long human inquiry into the origin of the solar system, the formation of planets, and the appearance of life has been impeded by the fact that we know of only one solar system and only one planet in it that has life. Is there in fact only one solar system, and only one life-bearing planet in the universe, or are there many? Do solar systems exist around other stars? Do they contain planets like the Earth? Do planets around other stars, Earthlike or not, have life? The answers are probably to be found far beyond Pluto, beyond the reach of spacecraft.

We suspect that planetary systems are a frequent accompaniment to the process of star formation, but the theories are imperfect, and hard facts are few. To understand our own solar system fully, we must discover and study similar planetary systems around other stars or (a more difficult task) demonstrate convincingly that they are not there.

Our generation is the first in all human history to have the technical skills to attack these questions directly, using Earth-based telescopes to probe the regions around nearby stars. In the last few years, we have detected indications, but not proof, that planetary systems may exist around at least some of the nearest stars. Both ground-based and Earth-orbital observations have detected disks of solid matter around several stars, notably Vega, Fomalhaut, and Beta Pictoris. The material around these stars seems to be dust-like, and no planet-sized bodies have been detected.

To establish the existence of planets, whether Jupiter-sized or Earth-sized, around other stars, we must undertake specialized, technically demanding, long-term observations. Because of the extreme distances to even nearby stars, these searches must be performed using powerful telescopes and sensitive instruments on the Earth's surface or in Earth orbit.

Technical studies for such a program, called "Toward Other Planetary Systems" (TOPS), are already well ad-

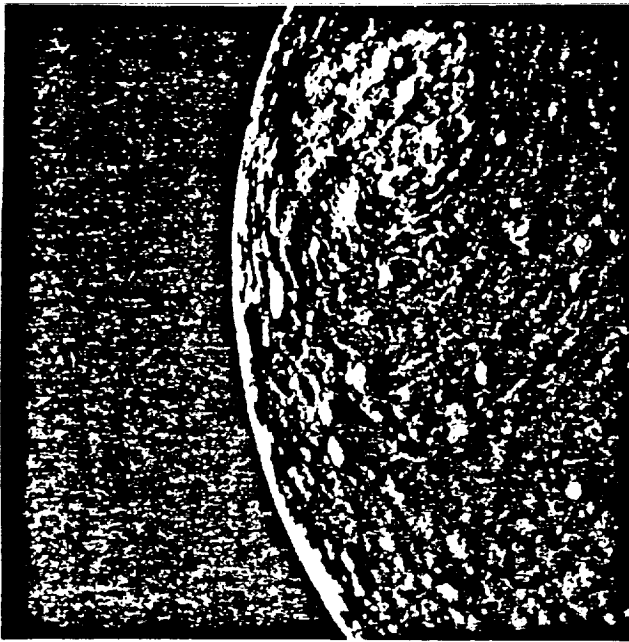


Figure 15. This Voyager image of Callisto shows a global scale, ancient scar of an impact that occurred when the icy crust was soft and pliable. Enormous rings surrounding the central target zone record the crustal response as the enormous impact cavity collapsed.

vanced. Several approaches are being evaluated, falling into two general categories, *direct* and *indirect* methods.

Direct measurements have the objective of obtaining actual images, and perhaps even spectral measurements, of planets around other stars. This is a formidable task. At the distance of even the nearest stars, the small amount of light reflected from even large planets is hidden in the more intense light of the star, and the technical problem is equivalent to seeing a candle flame held next to a searchlight a mile or so away. Nevertheless, this detection is attainable as the scale and capabilities of space-borne instruments develop.

One approach is to use innovative visible imaging techniques using supersmooth optics and coronagraphic methods for cancelling the light of the central star. An alternative approach is to make the observations in thermal infrared wavelengths, where the planet's brightness is comparable to that of the parent star, making the planet more easily detectable. These approaches can be initially demonstrated at the very best ground-based telescopes, using adaptive optics technology and optical imaging interferometry. However, they are most powerful in space, where the instruments are free of atmospheric distortion and where stray radiation can be reduced to a minimum.

One aspect of the direct approach that can be carried out almost immediately on the ground, however, is the study of circumstellar nebulae, especially at infrared wavelengths. For this search, a large telescope is essential, and

the opportunity has arisen to use a share of the second 10-meter Keck Telescope on Mauna Kea in Hawaii. This instrument will be built close to the first Keck 10-meter Telescope, which has just reached the "first light" stage and is approaching completion. This initiative, TOPS 0, the first of four phases of the TOPS program, is described in detail in Volume V of this series.

Indirect measurements, instead of imaging directly, attempt to establish the existence of planets around other stars by detecting the influence of the planet on the star itself. The star and its planets move about their common center of mass, and the resulting "wobble" of the star should be detectable. Because stars are massive and planets are not, this effect is tiny and can be detected only with careful measurements of either the position of the star (*astrometry*) or of small shifts in its spectrum caused by the movements along the line of sight (*Doppler effects*).

Ground-based astrometric and Doppler measurements are difficult, particularly because of the disturbing effects of the Earth's atmosphere, and these observing programs have not detected any definite planetary motions. However, this situation could change in the next few years. Studies indicate that the use of the two Keck Telescopes as a large interferometer in the superb seeing conditions on Mauna Kea will yield significant improvements in astrometry. The Keck II can also be used for filled-aperture astrometry. One can then envision an extensive and systematic ground-based observing program that would use new observational technologies from the best observing sites. Such a program could survey the approximate 400 stars within a distance of 16 parsecs from the Sun for the presence of Jupiter-sized planets.

The next step, the TOPS 1 phase about a decade from now, will be to place astrometric instruments in space, where they will be entirely free of atmospheric disturbances. Such instruments would be sensitive enough to survey the same 400 nearby stars for Uranus-sized planets, and they could extend the search distance far beyond that achievable from the ground.

2.3 Program Structure

From this discussion of our progress in solar system exploration, it is easy to appreciate the many exciting opportunities from which to choose in proceeding to the next levels of investigation. Clearly, a systematic approach must be used to be able to proceed in a rational cost-effective manner. Within such an approach, already discussed above, is needed a program structure. Specific recommendations of implementation for a strategic plan can then be made within the context of this program structure.

The solar system exploration program is made up of three specific elements: (1) Research & Analysis (R&A), (2) Flight programs, and (3) Mission Operations & Data Analysis

(MO&DA). This structure was refined by the Solar System Exploration Committee in a series of strategic planning activities conducted in the 1980s by dividing the flight program into a core program and an augmentation program in order to reflect different levels of flight program capability and cost. The core program consisted of Planetary Observer missions to the inner planets (moderate class missions), and Mariner Mark II missions to the outer planets and primitive bodies (major class missions). The augmentation program consisted of ambitious, exciting, but also very expensive missions — such as sample returns from Mars and a comet.

In the 1990s, there has been an evolution of OSSA program structure resulting from the development of an OSSA Strategic Plan with new definitions of mission classes as major, moderate and small; and the division of the OSSA program into a core science program and two augmentations based on presidential initiatives in Global Change and Space Exploration — Mission to Planet Earth and Mission from Planet Earth. The solar system exploration program structure is readily mapped into this new OSSA structure by placing the Mariner Mark II missions into the major mission category, the former Observer missions into the moderate mission category, and the new Discovery class of planetary missions into the small mission category. The TOPS program represents a new expansion of the boundaries of planetary science to embrace planetary systems around other stars, and requires a unique and evolutionary approach to the observational component of the solar system exploration program. It is therefore given a category of its own.

The Mission from Planet Earth element of the OSSA program is intended as an augmentation to the core science program in order to implement the president's initiative. The solar system exploration program's augmentation program of the 1980s naturally evolves into a Mission from Planet Earth augmentation of the 1990s, especially since one of the featured augmentations is a Mars sample return mission. The Solar System Exploration Division has been developing lunar and Mars scientific exploration programs over the past decade as core science missions, including the Mars network and Lunar Observer missions, which it intends to carry out even in the absence of a Mission from Planet Earth initiative. These missions are listed both as core science missions and as the solar system exploration program's contributions to the early phases of Mission from Planet Earth — contributions that will provide the information needed to plan the subsequent human exploration of these worlds at the same time that they are carrying out exciting scientific measurements.

The Solar System Exploration Division aggressively supports the Mission from Planet Earth initiative, and expects to play a leadership role both in the definition of the

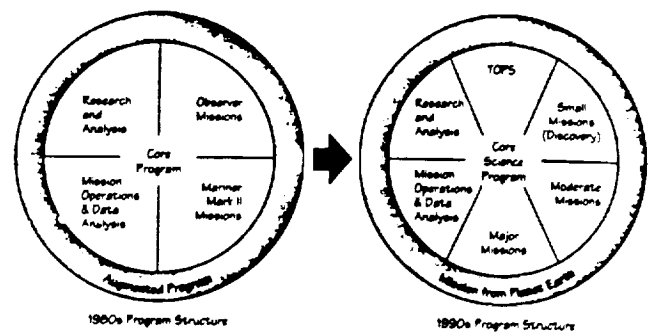


Figure 16. Solar System Exploration Division Evolution of Program Structure.

scientific exploration objectives of the president's program and in implementing the robotic elements of the program.

The Mission from Planet Earth initiative would be well served by a charter in the form of a plan for the scientific exploration of the Moon and Mars using humans and robots together, and this plan should:

- have clearly defined science goals as an integral part of MFPE
- assure continued progress in already established science objectives for the Moon and Mars
- define robotic roles and missions to support these objectives
- identify benefits of robotic missions to human exploration
- determine robotic technology developments critical to MFPE success
- enhance Moon/Mars exploration through an MFPE augmentation.

2.4 Fundamental Precepts of the Strategic Plan

An effective exploration strategy emerges from collectively considering and balancing the many factors affecting informed planning. These factors include priorities in ongoing exploration opportunities, the current programmatic climate in which we find ourselves, the planning rules set forth by OSSA, and the structure of the program within which the strategy is to be framed. The overarching theme of our plan — "Preparing the way to the New Frontier of the 21st Century" — provides the backbone for the strategy.

The Solar System Exploration Division's strategy for the 1990s encompasses five fundamental precepts:

- (1) **Execute** the current program.
- (2) **Improve** program and community vitality.
- (3) **Initiate** small low-cost planetary missions.
- (4) **Initiate** new major/moderate missions.
- (5) **Prepare** for the next generation (21st Century) of missions.

Each of these precepts entails a series of actions that collectively define an attribute of the Strategic Plan. Within each precept these actions are as described below.

1. Execute the Current Program

In the last several years, planetary exploration has regained the momentum that it lost during much of the 1980s. It is imperative that this level of flight program activity be sustained in the 1990s. Magellan mapping of the Venus surface must be maintained through several additional cycles to complete gaps in the radar mapping, to improve the gravity model of the planet, to obtain stereo imagery, and to further study specific features of the now-revealed Venus surface. Galileo, now en route to Jupiter, will make several close encounters of asteroids before reaching the giant planet in 1995. This first exploration-level mission to the outer planets promises to give us new insights into the physical properties and dynamics of the entire Jovian system and is a key step forward in solar system investigation — we must overcome the current difficulties with the spacecraft antenna and press on to a successful encounter. Mars Observer will provide us with the critical global databases of the planet's surface composition and climate necessary to both further the scientific understanding of Mars' evolution and to make informed preparations for the MFPE initiative. We must proceed with its launch next year as planned.

CRAF/Cassini is the first major mission to be executed under the current OSSA strategic planning rules. It is also the first development of the Mariner Mark II spacecraft design concept, which is key to the implementation of much of our exploration-level science of small bodies and the outer solar system for the foreseeable future. Both the comet rendezvous and Saturn orbiter/Titan probe science investigations of the CRAF/Cassini missions are top priority objectives of our Core Science Program. It is crucial to our ongoing strategy that we complete the development of this flight project within budget (capped by Congress at \$1.6B) and schedule.

2. Improve Program and Community Vitality

Although the flight program activity has been firmly reestablished, underlying research, data analysis, and mission operations support is still deficient. The erosion of R&A funding within OSSA during the 1980s was particularly damaging to the planetary science community. It is now extremely urgent that base capabilities in research and analysis be revitalized so that the community is prepared to fully apply the new data beginning to flow from the backlog of missions recently launched. To this end, it is our strategy to aggressively pursue a number of enhancements to our base program in the near term.

First, we must continue R&A recovery augmentations to reinstate an acceptable base level of funding. Second, we plan to initiate specific R&A thrusts with each new start to better engage the science community's involvement during flight project development. This action is seen as an effective means of best preparing for the flood of new informa-

tion released with each successful planetary encounter. Third, we want to introduce data analysis new starts to provide the funding means to implement the actual community-wide analytical activities associated with the large amounts of data now anticipated from our flight program. In order of priority these initiatives will address: Venus (Pioneer Venus Orbiter, Magellan, and Galileo encounters), Asteroids (Galileo and CRAF/Cassini encounters), Mars (Mars Observer mapping), and the Outer Planets (Galileo and Cassini orbit and atmospheric entry activities).

A new element of solar system exploration is the TOPS (Toward Other Planetary Systems) initiative, responding to the added exploration goal of searching for planets of other stars. The fourth revitalization action is to establish the TOPS program, initially within the R&A program as part of our ground-based observational activities. Fifth, we will pursue enhancement of the capabilities to support Mars Observer operations, primarily to utilize the full capabilities of this spacecraft and to maximize the potential science return from this mission. Finally, we need to assure the smooth and timely transition of Multi-Mission Operations software in order to effectively accommodate the growing number of projects in flight during the coming decade.

3. Initiate Low-Cost Planetary Missions

The OSSA decision rules for strategic planning specifically call out the objective of small mission new starts, preferably every year. Within the Core Science Program we have defined a small mission program called Discovery. In concept, such efforts are to be missions of opportunity launched in 3 years or less, and costing less than \$150M each. They may be Earth-orbital payloads, interplanetary probes, or instruments contributed to foreign missions. We are in the process of confirming the cost limit on a candidate set of missions and hope to start the first Discovery project as soon as possible. Given the current budgetary environment of space program funding, the addition of Discovery-class missions to planetary exploration is seen as an important means of sustaining our flight program development activity for the next several years.

4. Initiate New Major/Moderate Planetary Missions

Also part of the OSSA decision rules is the intent to initiate a major or moderate mission within OSSA each year. For its part, the Solar System Exploration Division must realize at least one major and several moderate new starts by the mid-1990s to maintain the balance and momentum of its present program. For overall program balance, the timing and priorities of planetary flight project opportunities are such that the major new start will be chosen from small body and outer planet missions within the Core Science Program. The moderate new starts will focus on lunar and Mars missions and could be started either as part of an MFPE initiative or the Core Science Program.

5. Prepare for the Next Generation of Missions

This final precept of our strategy recognizes the significant advantage of enabling technologies in the definition and implementation of the future solar system exploration program. Without new technologies, our options are limited by lack of capability and often by increased cost.

Because planetary spacecraft must leave Earth orbit and travel throughout the solar system, requirements for launch vehicles and spacecraft propulsion are both unique and demanding. Once in space, the operating environment is severe; launch accelerations and vibration, temperature extremes, vacuum, and radiation must all be overcome. Missions to distant planets require long travel times, so that spacecraft and instruments must operate for years or even decades. Long communication times mean that the spacecraft must be largely self-sufficient and that mission operations must be planned long in advance. The increasing data returns, even from current missions like Magellan and Galileo, require new and more efficient methods of collecting, storing, managing, distributing, and interrelating huge amounts of information.

As our explorations have progressed, both the scientific goals and the operating requirements for future missions have increased. An essential part of the future planetary exploration program must be the identification and development of new techniques for exploring space successfully, efficiently, and cost-effectively.

Developing a new technology — instrument, computer, spacecraft subsystem, or launch vehicle — to the point where it can be convincingly included in a new mission start can take as much as 5 years; another 5 years or more may pass between the start of a new mission and its launch. This means that as much as 10 years can elapse between the time a needed technology is identified and the time that the spacecraft carrying it is launched. Simply put, the new technologies needed for missions to be launched after 2000 need to be identified and developed starting *now*.

Technology development for planetary missions is shared between two organizations in NASA: the Solar System Exploration Division and the Office of Aeronautics, Exploration and Technology (OAET). OAET is charged with developing "generic" technologies, such as new propulsion concepts, instrument sensors, computers, and data management systems, which can be used in a wide range of different projects. The Solar System Exploration Division is responsible for producing the more focused technical developments needed for specific planetary missions, and it does so by combining OAET-funded technologies with more specific developments supported by Division funds.

This arrangement requires that the Solar System Exploration Division and OAET cooperate closely to identify and develop essential new technologies. As part of this strategic plan, a formal process to insure such effective cooperation

is now being established. In the initial discussions, the Solar System Exploration Division will determine the science requirements for its planned missions and will then use those requirements to identify necessary technical developments. The two organizations will then decide which developments will be carried out by OAET and which by the Solar System Exploration Division. In addition, the Solar System Exploration Division will strengthen its existing program for technical development, particularly in the area of spacecraft instruments. During the next few years, this process will be strengthened to ensure that new technical developments will be available in time to support the study, approval, and initiation of new planetary missions.

Two areas of technology are of particular importance to solar system exploration and are to be emphasized as part of our strategic plan: (1) landed robotic science techniques, and (2) mission-enabling delivery systems including propulsion, aero-entry, landing, mobility, and return capabilities. These vary from mission to mission, but are found in some combination on most future high-priority missions. We also must participate in the continued definition of the MFPE initiative since its most obvious near-term impact is to set technology development priorities.

These then are the five fundamental precepts of our 10-year strategy. Together they form the basis for the definition and recommendations of our plan for FY 1994 to FY 2003. It should be apparent that these are an integrated set of requirements to a well-founded plan. Take any of them away, and the resulting plan will immediately show weaknesses and lack of balance. The plan we recommend below seeks to consider each and all of these precepts within the guidelines of OSSA's larger planning effort as well as the very real programmatic constraints within which we all must operate today.

3. Proposed Future Solar System Exploration Program

3.1 Ground-Based Activities: Building Up the Base

Deep-space missions are the most spectacular part of planetary exploration. But, like the visible tip of an iceberg, these missions exist only because they rest on a firm foundation of less conspicuous ground-based activities: laboratory research, theoretical studies, astronomical observations, mission operations, analyses of data from previous missions, and advanced studies of future missions, spacecraft, and instruments.

The missions that fly today are possible because these ground-based activities were actively supported in the past. The more demanding missions of the future will be neither possible nor scientifically productive unless these essential base activities can be continued and strengthened, starting now.

Ground-based activities provide essential scientific expertise for planning missions and for interpreting the data

obtained from them. Ground-based research also provides information about the solar system that spacecraft cannot obtain: long-term synoptic observations of distant planets, precise chemical data from meteorites, and age measurements on returned samples that can establish the exact geological history of sampled bodies. Theoretical studies and laboratory experiments help interpret the data returned by spacecraft. Over the past years, these research activities have forged a strong link between NASA and the university community, so that they contribute directly to scientific education and to the entry of new planetary scientists into the field.

During the last decade, all ground-based planetary activities have been severely eroded. The scientific component has been especially hard-hit. Prolonged level funding has combined with continuing inflation to decrease the number and scope of investigations that can be supported. The high cost of modern scientific instruments has made it impossible to replace obsolete laboratory equipment (much of which dates from the Apollo Program in the early 1960s) or to purchase new instruments with capabilities that are routinely available elsewhere. These conditions, which are common to all fields of space science, were discussed in detail in the 1986 SESAC report, *The Crisis in Space and Earth Science*.

Within the Solar System Exploration Division, ground-based activities are divided into three areas: Research and Analysis, Mission Operations, and Data Analysis. It is essential to strengthen and expand all these areas, so that they can adequately support and justify the ambitious planetary missions of the future. Significant new resources must be provided to strengthen existing science disciplines and to support new research areas, many of them interdisciplinary, that have evolved from the results of past planetary exploration. New mission operations procedures must be developed to handle more complex and demanding missions more efficiently. And organized data-analysis programs must be established to effectively use the large amounts of interdisciplinary data that the missions of the 1990s and beyond will send back to Earth.

The near-term plan for this non-flight element of the solar system exploration program is summarized in Table 3 and described briefly below.

3.1.1 Research and Analysis

This area includes the planetary science research programs: planetary astronomy, planetary atmospheres, planetary geology/geophysics, and planetary materials/geochemistry. It also includes: (1) the Advanced Studies program for studies of future missions; (2) the Planetary Instrument Definition and Development Program (PIDDP), which supports the development and testing of concepts for future flight instruments; (3) the Planetary Data System, which provides for the preservation of mission data in ac-

tive archives, using formats that are easily accessible to scientists and others who need the data; and (4) the Origins of Solar Systems program, which supports studies that explore areas of science that lie between astrophysics and planetary science.

The Solar System Exploration Division intends to strengthen these programs by establishing a series of new long-term initiatives, at least one each year for the next several years. The modest resources for these initiatives will help achieve several essential goals. They will build up the existing research base, which has eroded severely during the past 10 years. They will provide support for new interdisciplinary fields of research, many of which now cut across Solar System Exploration Division disciplines and even across traditional boundaries between the Solar System Exploration Division and other OSSA divisions. Finally, they will emphasize the educational contribution of university-based space science and will help train a new generation of young scientists.

This series of Research and Analysis initiatives was actually begun in FY 1990 with the Origins of Solar Systems program to explore the interdisciplinary questions of planetary formation from the viewpoints of both astronomy and planetary science. The schedule for future initiatives is:

FY 1993. Toward Other Planetary Systems (TOPS). The TOPS 0 initiative is the first phase of a contemplated three/four-phase program directed toward the detection and study of other planetary systems. This first phase includes NASA's contribution to the development and operation of the Keck II 10 m optical/IR telescope on Mauna Kea. The Research and Analysis component of the initiative will support those scientific investigations that are essential to this reconnaissance phase of the program.

FY 1994. Advanced Computation and Visualization. Advanced computational and visualization capabilities offer new, powerful opportunities for extraction of scientific information from planetary data sets and from computer models of complex systems. This program will provide planetary scientists with access to these resources and will permit them to simulate computationally the origin and dynamical and chemical evolution of the solar system and its components.

FY 1995. Instrument Development Augmentation. The already demonstrated value of the Planetary Instrument Definition and Development program will be enhanced manifold by a modest augmentation. Value added by the augmentation will include reduction of cost growth of selected flight instruments and availability of developed state-of-the-art instruments for new classes of missions contemplated for flight in the next decade.

FY 1996. Centers for Laboratory Study. Experimental and analytical studies essential to the understanding of plan-

etary data are lagging because of the lack of facilities. Although existing PI capabilities are being upgraded at a modest rate under the Planetary Instrument Upgrade Program, establishment of advanced state-of-the-art, integrated instrumental systems necessary to advance the science is precluded by funding limitations. This program would provide for the establishment of centers of laboratory planetary science available to all qualified experimentalists where the complex analytical studies necessary in modern science can be conducted.

FY 1997. Planetary Systems Science. This program will support comparative and multidisciplinary studies of the planets as total systems to reveal fundamental physical and chemical processes involved in their formation and evolution and to explain why each evolved to its final unique state. Data from all previous missions will be utilized as will methods of interactive analyses made possible by modern computational techniques.

3.1.2 Mission Operations

Current and future planetary missions will place ever-greater demands on ground operations, communications, and data management capabilities. Starting with Magellan, and continuing through Mars Observer, Galileo, CRAF,

and Cassini, missions will be more sophisticated, and operational requirements will be correspondingly more complex. Outer planet missions will involve longer travel times to their targets. Orbital missions will have longer lifetimes in orbit. Data returns will be much greater. (Magellan has already returned more data than all previous planetary missions combined!) Data streams will come from multiple instruments and will require multidisciplinary management and distribution.

Because of the high cost of building and launching spacecraft, resources allocated to efficient operations and science data collection are the most cost-effective way of maximizing the science returns. The Solar System Exploration Division plans a group of small initiatives in FY 1993 to increase the science data return from two current missions and to strengthen mission operations capabilities for the future. These initiatives are:

Magellan Extended Mission. The Magellan mission, launched in 1989 to make a radar map of the cloud-hidden surface of Venus, has been an visible planetary achievement and one of NASA's most visible successes in recent years. After less than a year of mapping, Magellan has already revealed Venus to be a complex, active, and exciting world. The planet's surface contains a baffling variety of

Table 3. Solar System Exploration Division Near-Term Plan for the Non-Flight Program.

Fiscal Year Initiatives						
	'93	'94	'95	'96	'97	'98
Research and Analysis	▲ Toward Other Planetary Systems	▲ Advanced Computation and Visualization	▲ Instrument Development Augmentation	▲ Centers for Laboratory Study	▲ Planetary Systems Science	
Mission Operations	▲ Magellan Extended Mission ▲ Mars Observer Enhancement ▲ Multimission Software Transition					
Data Analysis	▲ Venus (Galileo, Magellan, and Pioneer Venus Orbiter)	▲ Asteroids (Galileo and CRAF/Cassini)	▲ Mars (Mars Observer)	▲ Outer Planets (Galileo and Cassini)		

landforms: high plateaus, contorted mountain ranges, fields and channels of frozen volcanic lavas, and huge complex impact craters. The surface is geologically young, perhaps only half a billion to a billion years old, indicating that Venus is an active planet where geological forces periodically resurface the crust. Venus is now established as an active planet, more active than Mars, less active than Earth, and geologically different from both.

When the current mission plan ends in January 1992, Magellan will have mapped 96 percent of Venus' surface. To take advantage of Magellan's continuing successful operation and to improve our knowledge of the complexities of Venus, we plan an Extended Mission through FY 1995. The relatively modest resources required for the Extended Mission will produce a major increase in scientific knowledge about a complex and mysterious world. During the Extended Mission, Magellan will map the remaining 4 percent of the planet to provide 100 percent coverage. It will make detailed studies of important and puzzling regions identified in the earlier mapping, using different radar techniques to obtain higher-resolution maps of landforms and topography. The Extended Mission will also provide improved measurements of Venus' gravity field, so that its internal structure and geological activity can be better understood.

Mars Observer Augmentation. A small augmentation is planned to increase the data return from Mars Observer, which will enter Mars orbit in September 1993 for a 2-year global mapping mission. The augmentation will improve communications and data management, and will significantly increase the science return.

An additional enhancement to Mars Observer operations is also proposed in the context of Mission from Planet Earth. In particular, the enhancement will increase the amount of high-resolution imagery that can be obtained, thus producing a major benefit for the scientific study of Mars and for planning future human operations on its surface.

Multimission Software Transition. The Solar System Exploration Division's long-term plans for operating future planetary missions, some of which must be operated simultaneously for long periods, is to develop a single Multi-Mission Operations Facility that can handle all missions, rather than continuing the less efficient method of developing (and eventually dismantling) individual operations centers for each mission. This initiative will support the major development of operating software for multiple missions, together with the phasing in of both software and new operations during the next few years. This process is complicated by the fact that some current missions are operating in the earlier (individual) manner. The transition must, therefore, be carried out carefully and smoothly, but the software development and phasing in are essential for efficient and adaptable mis-

sion operations for future missions, both in the last years of this century and in the first years of the next.

3.1.3 Data Analysis

The post-mission analysis of data returned from planetary missions is an essential part of a strong and continuing planetary exploration program. Data from a single mission may remain scientifically valuable for years or even decades after the mission has ended, as the data are reexamined from new perspectives or combined with data from subsequent studies. The Viking Mars data, returned in the late 1970s, are still providing important scientific insights, while reexamination of the Apollo data, collected even earlier, will be an important step in planning the future exploration of the Moon by spacecraft and human beings.

Continuing data analysis provides important benefits. It generates a steady stream of new scientific results, even during periods when missions are not flying. It helps maintain momentum, and it keeps an essential scientific community together to provide advice on future missions. Data analysis programs are an effective way to contribute to university-based science and education, and they provide a means for graduate students and young scientists to enter planetary science research.

To ensure that the future Data Analysis program is adequately matched to the ambitious planetary missions of the 1990s and later, we plan small but important initiatives in this area during the next few years to make the data-analysis process more systematic and effective. The main goal of these initiatives is to create a prompt and smooth transition from mission operations into data-analysis activities. Because future mission data will be released for general use only 6 to 12 months after being obtained, establishment of data-analysis programs cannot be delayed until the missions themselves are over; these programs must be established in parallel with mission development and operations. The new initiatives will also make it possible to support projects that study a single planet, or a group of planets, using data from several different missions, some of which may be widely separated in time.

We plan to start one data analysis initiative each year for the next few years and to continue them for at least several more years. The nature and timing of these activities reflect the status of individual missions. A single initiative can be continued to allow for study of the data from new missions. The plan for these initiatives is:

FY 1993. Venus Data Analysis. This effort will support the widest possible examination of the surface of Venus, using the tremendous amount of new data being returned by Magellan. It will also include atmospheric studies based on older data obtained by the Pioneer Venus Orbiter since 1978 and by the Galileo flyby in 1990.

FY 1994. Asteroid Data Analysis. This activity will support data analysis from the first close-up observations of asteroids during the Galileo flybys of October 1991 (asteroid Gaspra) and August 1993 (Ida). The initiative will then continue, using data provided by the asteroid flybys of CRAF and Cassini in the later 1990s.

FY 1995. Mars Data Analysis. Data from Mars Observer will become generally available in 1994-1996. This initiative is timed to support a wide range of scientific analyses of the data, which will complement and extend the range of investigations being carried out by the Mars Observer scientists themselves.

FY 1996. Outer Planets Data Analysis. This general initiative will support comparative studies of data collected from the four giant planets of the outer solar system. It is specifically timed to support analyses of the new data about Jupiter obtained from the Galileo mission after its arrival at Jupiter in December 1995. Later, the same initiative will accommodate data from the Cassini mission at Saturn.

The small initiatives planned for these three critical ground-based activities — Research and Analysis, Mission Operations, and Data Analysis — are essential to maintaining a strong, flexible, and dynamic science base to support planetary exploration during the rest of the 1990s and beyond. The modest resources required will provide benefits far out of proportion to the funds involved. These initiatives, established carefully and systematically during the next few years, will insure the continued availability of a strong planetary science community to plan and support

future exploration of the solar system. They will also help continue university involvement in NASA's programs, maintain high-quality education in planetary science, and train the new scientists who will carry on the exploration of the solar system in the 21st Century.

3.2 Flight Missions

The next logical flight missions for planetary exploration were summarized earlier in this document. However, the number of these missions greatly exceeds the number of new starts expected in the next few years. A subgroup of these missions has been selected for proposed new starts in the FY 1994 to 1998 period, based on programmatic goals, technical readiness, and anticipated resources.

Table 4 shows candidate new start missions for the planetary component of the O SSA Strategic Plan. The missions are part of a balanced program to study all types of solar system objects (inner planets, outer planets, and small bodies), together with Mission from Planet Earth, searches for extrasolar planets, and Earth-orbital facility instruments. Missions proposed for FY 1994-1998 are given with the earliest new start year; candidates for FY 1999-2003 are the remaining flight projects of the 10-year plan that have not yet been integrated into a flight schedule.

3.2.1 Mission From Planet Earth

Our proposed near-term components of the Mission from Planet Earth strategy are also our highest priority candidates for the inner planets category of core science mis-

Table 4. Solar System Exploration Division Ten Year Flight Mission Plan.

Mission Element	Recommended Missions FY94-FY98	Candidate Missions FY99-FY03
Mission From Planet Earth	Lunar Observer (94)* Mars Network (95)	Lunar Surface Science Mars Sample Return
Inner Planets		Mercury Orbiter Discovery Venus Probe
Outer Planets	Pluto Flyby/Neptune Orbiter (96)	Uranus Orbiter/Probe Jupiter Grand Tour
Small Bodies	Discovery Near Earth Asteroid Rendezvous(94)	Comet Nucleus Sample Return Main Belt Asteroid Rendezvous
Extrasolar Planets	Toward Other Planetary Systems (TOPS) [Keck II] (93)	TOPS [Orbital]
Orbital Science/ Space Station	Discovery Orbiting Planetary Telescope (96)** Cosmic Dust Collection Facility (97)	

* New start dates (earliest)

** One candidate among several for second Discovery mission.

sions. These are both moderate class missions: Lunar Observer and a Mars lander network mission titled MESUR (Mars Environmental Survey).

Lunar Observer, recommended for a new start in FY 1994, is principally a global survey mission aimed at measurements of geochemistry, petrology, gravitational and magnetic fields, and altimetry. This mission is critical for both science and human exploration. The mission will also obtain images for a geodetic map of the Moon. Additional potential objectives are higher resolution imaging, an atmospheric survey, and microwave radiometry to estimate heat flow and regolith thickness.

Satisfying these objectives will not only greatly advance our understanding of the Moon, but it will also provide the global context we require for human exploration. Despite the wealth of lunar data returned from Apollo, our knowledge of the Moon as a whole is limited. The Apollo orbital geochemistry data cover only the narrow equatorial command module ground-tracks. Geochemical and petrologic data are needed to select the most promising sites for human exploration and to evaluate the availability of resources in lunar surface material. Our knowledge of the farside gravitational field is also limited, since measurements require two spacecraft in lunar orbit. The Lunar Observer, through a small subsatellite, will supply these data, which are essential for optimizing lunar spacecraft design.

A Mars global network mission is proposed for initiation in FY 1995. The overall goal of this mission is to emplace a network of small stations on the martian surface. The functions of these stations will be to (1) determine the global seismicity of the planet and the planet's internal structure, (2) determine the global circulation pattern of the atmosphere and surface meteorological conditions, (3) determine the major and minor element chemistry of representative near-surface rocks and soils, (4) determine low temperature mineralogy of representative near-surface materials, (5) determine the fine-scale structure of the surface at representative locations, and (6) increase our knowledge of the structure of the middle and upper atmosphere. Although the prime justification is scientific, much of the information returned, including the nature of the surface at spacecraft scales, would aid human mission planning.

Our approach to the network mission is the Mars Environmental Survey (MESUR), consisting of several launches on Delta expendable launch vehicles. Four small probes would be launched on each Delta, each probe flying independently to Mars. After atmospheric entry, a lander carried by each probe would descend by parachute and make a semi-hard landing. Each lander would carry descent and surface cameras, a seismometer, a meteorology package, an alpha/proton/X-ray analyzer, a simple thermal analysis device with evolved gas analyzer, and a simple entry sci-

ence package. Power would be provided by radioisotope thermoelectric generators (RTGs). In the simplest implementation, no sample acquisition device is included; the analytical instruments are simply lowered to the surface.

The deployment strategy would include launches over at least three opportunities, spaced 26 months apart, leading to deployment of a full network of about 16 stations. In the most cost-constrained scenario, all stations would be the basic MESUR lander. Four would be launched on a single Delta vehicle at each of the first two opportunities, and eight would be launched on two Deltas at the last opportunity. A communications orbiter would be launched separately at the second opportunity. The lander lifetime must allow for simultaneous operation of the first and last stations.

3.2.2 Pluto Flyby/Neptune Orbiter and Probe

The Pluto Flyby/Neptune Orbiter and Probe program is our only major mission candidate for the next 5 years, scheduled to start in FY 1996. It was chosen because a principal objective — studying the atmosphere of Pluto before increasing heliocentric distance causes its collapse in the 2020s — can only be achieved using the next set of Jupiter gravity-assisted launch opportunities. These missions follow the CRAF/Cassini launches closely enough that they can take maximum advantage of the CRAF/Cassini Mariner Mark II spacecraft development.

The Pluto Flyby/Neptune Orbiter and Probe program uses two Mariner Mark II spacecraft, the same type employed for CRAF and Cassini. One spacecraft will go into orbit about Neptune and deploy a probe into the planet's atmosphere, with the objective of sampling to at least a 75 bar depth. Then, the main spacecraft will adjust its orbit plane to be retrograde, enabling repeated study of both Triton and Neptune's magnetosphere. Additional orbital adjustments will occur at each Triton flyby over the 4-year lifetime of the tour. Several flybys will be at sufficiently low altitude that direct sampling of Triton's atmosphere using a mass spectrometer will be possible.

The Pluto mission involves close flybys of both Pluto and Charon, including a fly-through of Pluto's upper atmosphere to enable direct measurements of its composition. Imaging coverage of Pluto's surface is nearly doubled by the inclusion of an imaging probe, released to precede the main spacecraft by one-half a rotation period. Images will begin to exceed HST's diffraction limit 5 months before closest approach; pickup ions from Pluto's atmosphere may be detected as early as 6 to 8 months out.

The strong scientific links between the Pluto and Neptune objectives are reflected in common payloads on the main spacecraft. Because both missions require a gravity assist from Jupiter, with close aim points, it appears feasible

to also conduct one or two close flybys of Ganymede or Callisto and to observe Io volcanic activity from relatively close distances during these flybys. These trajectories allow a total of at least 2 years combined cruise through the Jovian magnetotail, an unexplored region of high interest to plasma physicists. Other cruise opportunities include gamma-ray and infrared astrophysics, Chiron and Kuiper disk observations, and close encounters with the Earth-Moon system, Venus, and asteroids during the early segments of each flight.

3.2.3 Discovery NEAR

The Discovery Program is a new initiative of the Solar System Exploration Division to develop and launch low-cost (small) planetary science missions to complement current and planned major and moderate missions. The program will also include cooperative projects with other agencies and nations. Individual missions, or the Solar System Exploration Division's contribution to cooperative missions, are to cost no more than about \$150M (FY92\$) through launch plus 30 days, with an annual program expense level of about \$85M. All Discovery flight projects will be planned to launch within 3 years from project start. Discovery is a program and not a single mission; a significant number of important solar system investigations could fit within this cost envelope. The benefits of the program include rapid response to emerging scientific opportunities, participation in cooperative ventures with other agencies, increased breadth of activity in the solar system exploration program, and enhanced timeliness for new information return on important scientific questions.

Several candidate missions are being examined as early Discovery opportunities. A Near-Earth Asteroid Rendezvous (NEAR) is our choice for the first Discovery mission, scheduled to start in FY 1994. The NEAR Discovery mission will provide the first rendezvous with an asteroid, addressing fundamental science questions in a unique way. For example, such a mission could clarify the relationships between asteroids, comets, and meteorites, and may reveal clues to the nature of the planetesimals from which the terrestrial planets formed. Consequently, the primary scientific goals of such a mission are to characterize an asteroid's physical and geological properties and to infer its chemical and mineralogical composition. A focused set of a few remote sensing instruments can address these questions. Near-Earth asteroids are a distinct domain of diverse solar system bodies, related in as yet unknown ways to comets, main belt asteroids, and meteorites. They include primitive bodies from both the inner and outer parts of the solar system, as well as pieces of small bodies that were significantly altered during the early history of the solar system. Some may even be extinct comet nuclei.

3.2.4 Orbital Science

For FY 1997, we propose an orbital science initiative: the Cosmic Dust Collection Facility. This facility would trap particles of cosmic dust and simultaneously determine their velocities and trajectories. The particles would then be returned to Earth for detailed laboratory analysis. The Cosmic Dust Collection Facility is being studied as a possible payload attached to Space Station Freedom; the potential for launching it as a free-flyer is also being examined.

3.3 Technology Program

The next century of planetary exploration will see missions that existed only as impossible dreams at the beginning of the Space Age. These challenging missions and their ambitious scientific goals cannot be achieved with the "on-shelf" spacecraft, launch vehicles, instruments, and data management techniques that exist today. An essential part of the future planetary program is to identify and develop new technologies that will not only make these missions possible, but will also make them more efficient and productive.

Enabling technologies, which make possible missions or specific observations that simply cannot be done with available technology, include:

- *Sample Collection and Storage.* Sample return missions, whether to Mars or to the nucleus of a comet, need new robotic abilities to characterize, select, collect, store, and preserve a wide range of sample materials — rocks and soil from Mars, ices and dust from a comet nucleus. These techniques for remote sampling do not exist today, and their early development is as essential to sample return missions as are the spacecraft and launch vehicles themselves.
- *Autonomous Rovers.* "Smart" roving vehicles are essential for the future exploration of Mars, to analyze the martian surface at close range and to collect samples for return to Earth. The U.S. has only terrestrial and marine experience in this area. The only robot rovers placed on other worlds were the Lunakhod 1 and 2 landed on the Moon by the U.S.S.R. in the early 1970s. Developing such vehicles requires a whole range of new capabilities: autonomous operating software, mechanical systems, and efficient human/machine interactions. The new area of *microtechnology* is a promising field for investigation; if rovers and their equipment can be made smart and small, weight and power will be lower, and missions can be done more simply and cheaply.
- *Low-thrust propulsion,* either solar electric or nuclear electric. These techniques provide a small, long-lasting acceleration to a spacecraft, and they are essential for large missions into the outer solar system, in order to increase the payload weight or decrease the travel time. Such techniques are needed for several missions now under study, includ-

ing the Jupiter Grand Tour and a Main-Belt Asteroid Rendezvous.

Enhancing technologies, instead of making a mission itself possible, provide better ways of carrying it out — lighter and more rugged instruments, better sensors, faster data management, or more efficient spacecraft. Developments in these areas increase mission reliability, produce a higher data yield, or allow the more rapid management of larger amounts of data than is possible today. Several areas of enhancing technology are now under study, both in OAET and the Solar System Exploration Division, to determine how they can contribute to improving the missions of the 21st Century.

- *Instruments.* New optical systems are needed, especially to obtain the local high-resolution imagery needed to support Mission from Planet Earth or to detect other planetary systems through the TOPS program. Improved *passive detectors* for infrared and ultraviolet radiation, X-rays, and gamma-rays will provide more detailed and more accurate data about the mineral and chemical composition of planetary surfaces and about the nature of planetary atmospheres. Better *active sensors* such as radar and laser systems can provide more accurate data about planetary topography, surface roughness, and other surface properties. Finally, new developments are needed to reduce instrument weight, increase ruggedness, increase the rate or range of collected data, or improve processing and transmission of data. Such modifications are especially important for emplacing networks of small landed stations on Mars and other planets.
- *Spacecraft subsystems.* The next century's spacecraft must be technically improved as well. They must be more capable, more autonomous, more adaptable, and more enduring. Reaching these goals depends on more than a single technical innovation. A large number of different technical capabilities must be developed: more powerful computers, larger data storage systems, faster data management, smaller chemical propulsion systems, and new micromechanical systems for spacecraft operation. These technologies are highly "generic;" if developed for one mission, they can be applied to others, and they may even find uses far beyond the planetary program itself.
- *Mission Operations and Data Management.* The need to control tomorrow's spacecraft and to operate their payloads also creates special technical requirements. Future missions must operate for long periods of time and will produce incredible amounts of information from a large number of different and highly specialized instruments. The challenges of operating such spacecraft and of managing the data they return in an efficient and cost-effective way is already forcing us to design and develop new systems that will be very different from the ones we use today. Expert systems, neural

networks, photonics, mass storage devices/techniques, and automated/integrated data management systems are just a few of the relevant capabilities of interest. Fortunately, a continuing revolution in data management and communications is taking place, and many of these developments can be used to construct the next century's mission control centers and data management facilities.

The scientific and technical challenges of future planetary missions are well understood, and the necessary technical response is starting to take shape. With the new tools developed, and the preparatory activities of our 10-year plan, we can boldly attack the new space frontiers of the 21st century.